Gilbert F. Cochran

University of Nevada

Reno

Streamflow and Water Quality Effects of Groundwater Discharge to Steamboat Creek, Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Hydrology

by

Kenneth W. Shump

December 1985

The thesis of Kenneth W. Shump is approved:

____
Thesis Advisor

____
Department Chairman

____
Dean, Graduate School

University of Nevada

Reno

December 1985

ACKNOWLEDGMENTS

Financial and technical assistance instrumental in completing this report was provided by funds appropriated by the Nevada State Legislature to the Water Resources Center of the Desert Research Institute, by a grant from the Washoe County Public Works Department, and by CH2M HILL, Inc.

ABSTRACT

The rate of groundwater discharge to Steamboat Creek varies with location but is greatest adjacent to Steamboat Springs, at the Huffaker Narrows, and near the Truckee River confluence. Total groundwater discharge to the creek in the Truckee Meadows is estimated from current meter measurements to be within the range of 7.1 cfs to 28 cfs, with a mean of 17 cfs or 12,500 acre-feet per year (af/y).

The specific conductance of groundwater entering Steamboat Creek varies from a high of 2,400 μmho/cm near Steamboat Springs to a low of 600 μmho/cm near the Truckee River confluence.

The consistent B:Cl relationship in water samples supports the conclusion that Steamboat Springs is the primary source of boron in the Truckee Meadows. The As:SO_4 ratio in the Truckee Meadows is closer to the As:SO_4 ratio near Steamboat Springs than near the Virginia Range, indicating the springs as the origin of much of the aqueous arsenic in the Truckee Meadows.

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1.0 INTRODUCTION

1.1 LOCATION AND CLIMATE

Steamboat Creek is a north-flowing stream located in northwestern Nevada at the extreme western edge of the Basin and Range physiographic province (Figure 1). Originating as the outlet from Washoe Lake, Steamboat Creek traverses Pleasant Valley, Steamboat Valley, and upper (southern) Truckee Meadows, joining the Truckee River just east of Sparks. The study area lies almost entirely within the Truckee Meadows at an elevation of approximately 4,400 feet above sea level.

The climate in the study area is arid to semiarid. The mean annual precipitation at Reno is 7.32 inches. The period during which this study took place was drier than normal, with annual precipitation during the period July 1980 to June 1982 averaging 6.65 inches (Ganser, 1982). Precipitation in the Carson Range to the west far exceeds that in the study area. At an elevation of 8,800 feet on Mount Rose, precipitation averages 49.7 inches (Ganser, 1982).

A characteristic feature of dry climates is the large diurnal variation in temperature. Changes of 40°F or more

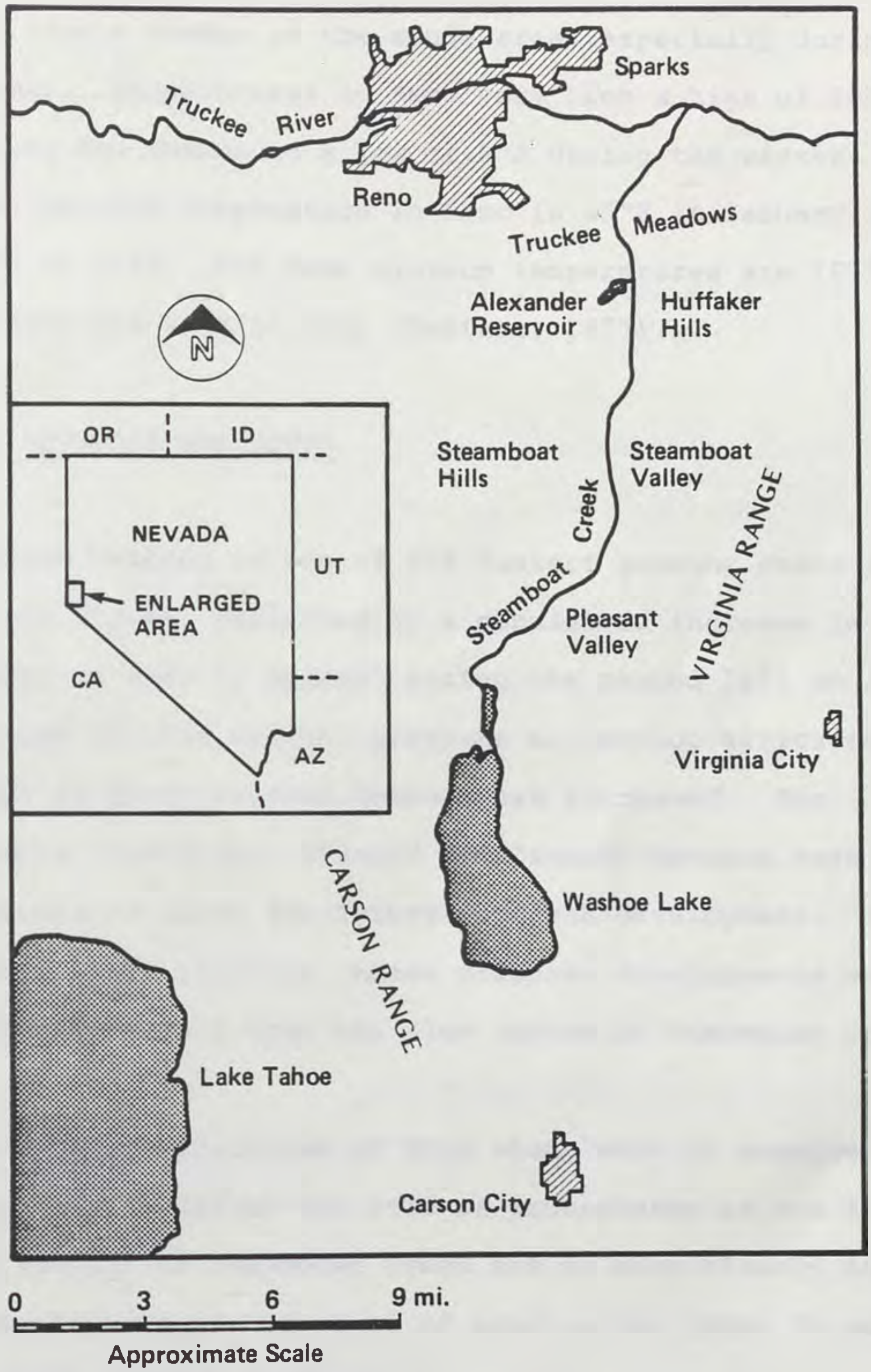

Figure 1
LOCATION OF
STUDY AREA

are fairly common in the study area, especially during the summer. Temperatures in Reno vary from a high of 100°F during the summer to a low of 0°F during the winter. The mean maximum temperature in Reno is 45°F in January and 91°F in July. The mean minimum temperatures are 18°F in January and 47°F in July (Ruffner, 1977).

1.2 PURPOSE AND SCOPE

Truckee Meadows is one of the fastest growing areas in the United States, reflected by a population increase in Washoe County of over 70 percent during the period 1970 to 1982. Because of this growth, pressure to develop agricultural lands in South Truckee Meadows has increased. For example, the Double Diamond and Damonte Ranches have been proposed as sites for future suburban development. It is likely that, if built, these proposed developments would have some effect upon the flow regime of Steamboat Creek.

The primary objectives of this study were to examine and more clearly define the role of groundwater in the flow and quality of Steamboat Creek and to more clearly delineate the potential sources of arsenic and boron in waters of South Truckee Meadows.

These objectives were met through a combination of field methods involving stream flow measurements, measurement of near-surface groundwater gradients, and water quality sampling.

1.3 PREVIOUS INVESTIGATIONS

Because of the presence of such landmarks as Steamboat Springs and the nearby Comstock Lode, this area has been studied periodically since the latter half of the nineteenth century. The first published geologic study including this area was completed by the Fortieth Parallel Survey (King, 1870, 1878). Louderback (1907) and Anderson (1909) described the geology of the area. Gianella (1936) summarized much of the early geologic work in this region.

In 1958, Thompson and Sandberg reported results of gravity surveys in the Truckee Meadows area, estimating the depth of alluvium at greater than 2,800 feet in the northern part of the basin and 1,000 feet in the southern part. Thompson and White (1964), White et al. (1964), and White (1968) published a series of U.S. Geological Survey professional papers on the regional geology, geologic history, and hydrology and heatflow of the Steamboat Springs system.

Of these three papers, White's 1968 paper dealing with the hydrology and heatflow of Steamboat Springs is the most relevant to this study. Based on isotopic ratios of deuterium:hydrogen and oxygen 18:oxygen 16, White concluded that the waters of Steamboat Springs are almost entirely meteoric, derived principally from small streams in the Carson Range. Using chloride mass-balance calculations, White concluded that the hot spring system discharged a total of approximately 1,130 gpm to the surface and groundwater.

Cohen and Loeltz (1964) published a U.S. Geological Survey Water Supply Paper on the hydrogeology and hydrogeochemistry of the Truckee Meadows area. Subtracting inflow from outflow in the Truckee Meadows south of Huffaker Hills, Cohen and Loeltz calculated that approximately 14 cfs of the total outflow was due to groundwater discharge to the creek. It was also suggested that groundwater discharge to the creek remains fairly constant throughout the year.

Bateman and Scheibach (1975) evaluated the occurrence of geothermal activity in Truckee Meadows. Although this topic had been previously covered by White (1968) and Cohen and Loeltz (1964), Bateman and Scheibach also investigated the effects of groundwater-thermal water mixing on groundwater quality. Nehring (1980) used various geothermometers to estimate a reservoir temperature at Steamboat Springs of 230°C. She also reiterates White's (1968) conclusion that recharge to the hot springs system is from the Carson Range, not from streams on the valley floor.

In addition to these papers, several reports have been published by the Water Resources Center of the Desert Research Institute on the hydrology and water use problems of the Truckee Meadows area. Cooley et al. (1971) collected hydrologic data from a variety of sources in order to model the water balance in the Truckee Meadows. Cochran and Fordham (1978) summarized water-related problems in the Reno-Sparks area, and Fordham (1982) updated the calculations of Cooley et al. (1971) using more recent information and an additional 10 years of records.

2.0 GEOLOGY AND HYDROGEOLOGY

2.1 REGIONAL GEOLOGY

The Steamboat Creek drainage basin is bounded to the east by the Virginia Range, an east-northeast trending mountain range, and on the west by the Carson Range, a spur of the Sierra Nevada. On its route northward from Washoe Lake to the Truckee River, Steamboat Creek flows through Pleasant Valley, Steamboat Valley, and Truckee Meadows. Steamboat and Pleasant Valleys are separated from Truckee Meadows to the north by Steamboat Hills.

The Carson Range is the dominant physiographic feature in the area. This range is separated from the main mass of the Sierra Nevada by a structural depression called the Tahoe-Truckee trough (Thompson and White, 1964). The Carson Range is roughly dome-shaped on its northeast side, but it is broken by several minor antithetic faults.

Metasedimentary and metavolcanic rocks are the oldest rocks exposed in the Carson Range. The age of these units is uncertain, but because they are intruded by Cretaceous rocks, they are believed to be of Triassic age (Thompson and White, 1964). Granitic rocks, ranging in composition from granodiorite to quartz monzonite, are extensively exposed in the Carson Range (Bonham, 1969). The granitic core of the range is unconformably overlain by a thick sequence of Tertiary extrusives, comprised mostly of the varied andesite flows, flow breccias, and agglomerates of the Kate Peak Formation (Bonham, 1969).

According to Thompson and White (1964) the structure of the Virginia Range is essentially a mirror image of the Carson Range. The western front of the range is bordered by major faults and is broken by several associated antithetic faults. As in the Carson Range, the oldest rocks exposed in the Virginia Range are Triassic metasedimentary and metavolcanic rocks (Bonham, 1969). These rocks, after metamorphism and deformation, were intruded by Cretaceous granitic rocks. Unconformably overlying this Mesozoic system is a very thick sequence of sedimentary and extrusive rocks, ranging from Oligocene to Pleistocene in age (Bonham, 1969). The Virginia Range differs from the Carson Range because extrusive rocks are more extensively exposed than in the Carson Range (Cohen and Loeltz, 1964).

Hydrothermal alteration, specifically bleaching, is widespread in the Cenozoic rocks of the Virginia Range. Bleaching may also be locally important in the Carson Range, but its occurrence is less extensive. Thompson and White

(1964) describe bleaching as a chemical reaction between rock and sulfuric acid. The acid originates from oxidation of disseminated pyrite or, in active thermal areas, from oxidation of hydrogen sulfide. Chemical changes that result from bleaching range from "...slight leaching of magnesium and calcium with partial oxidation of iron, through nearly complete removal of everything but alumina, silica, and a little iron, to removal of all the main constituents but silica" (Thompson and White, 1964). Thompson and White (1964) suggested that pyrite oxidation and bleaching are still active today, as reflected by the acidity--as low as 2.5 pH--of runoff from bleached areas.

2.2 LOCAL GEOLOGY

The study area is located in Truckee Meadows, a north-trending basin near the western edge of the Great Basin. Truckee Meadows is bounded to the south by Steamboat Hills and to the north by an extension of the Pah Rah Range and is divided into northern and southern sections by the Huffaker Hills.

Steamboat Hills is a low range trending east-northeast, with an antiform structure produced by tilted and warped fault blocks (Thompson and White, 1964). As with the major ranges of the area, relief is primarily due to major normal faults with minor associated antithetic faults (Thompson and White, 1964). Steamboat Hills is composed of Triassic metasedimentary rocks intruded by granodiorite, which are locally overlain by the Steamboat Hills Rhyolite, pediment gravels, basalt flows, and siliceous sinter near the hot springs (Bonham, 1969).

The Steamboat Springs are located near the northeastern end of the hills. White (1974) estimates that the hot springs have been active for up to 3 million years, and calculated their discharge as varying between 800 to 1,300 gpm (White, 1968).

The Huffaker Hills are an extension of the Virginia Range, separated from the range by a gap known as the Huffaker Narrows. Steamboat Creek flows near the western edge of this 1/5-mile-wide gap. The Kate Peak formation, extensively exposed in the hills, is cut by numerous northwest-trending faults (Thompson and White, 1964).

Truckee Meadows occupies a north-trending structural depression. Despite the large mountain ranges to the east and west, the basin is not a simple graben but was instead formed by a complex sequence of faulting, tilting, and warping (Thompson and White, 1964). On the basis of gravity surveys, Thompson and Sandberg (1958) have estimated the thickness of valley fill to range from a maximum of 2,800 feet in the northern part of the basin to a maximum of 1,000 feet in the southern part. Cohen and Loeltz (1964), on the basis of well logs, have suggested that the total thickness of valley fill may exceed 4,000 feet.

The valley fill consists of three major units: the Pliocene Truckee or Coal Valley Formation, a Pliocene to Pleistocene older alluvium, and a Pleistocene younger alluvium. The Truckee Formation is composed primarily of fine-grained unconsolidated and partially consolidated lacustrine deposits. Sediments include gravel, sand, silt, and interbedded diatomaceous clay. Alluvial fan and stream channel deposits are more common in the lower part of the formation where the sediments are commonly cemented with calcium carbonate (Cohen and Loeltz, 1964).

The older and younger alluvia, though lithologically similar, are differentiated by the following criteria: the older alluvium is structurally deformed, whereas the younger alluvium is not; the older alluvium is well dissected and forms the low foothills bordering the valley floor, whereas the younger alluvium is not appreciably eroded and is located primarily in stream channels and the valley lowlands; and the older alluvium exhibits a well-developed soil profile, whereas the younger alluvium's soil profile is only weak to moderately developed (Cohen and Loeltz, 1964). Hydro-Search, Inc. (1980), reports that in some areas of the Double Diamond Ranch a well-developed soil profile occurs in the younger alluvium, possibly because of a long history of flood irrigation. This situation probably exists in other irrigated areas as well.

2.3 HYDROGEOLOGIC PROPERTIES OF AREA UNITS

The consolidated rocks of the ranges bordering the study area, while hydrologically important as the source of the valley fill, have virtually no primary permeability and are not considered to bear water except in localized fracture zones (Cohen and Loeltz, 1964).

The Truckee Formation underlies much of the upper Truckee Meadows. Because of its porosity and thickness, this formation can store large amounts of groundwater. As is characteristic of largely fine-grained deposits, however, its hydraulic conductivity is low, and only small volumes of water are yielded to wells (Cohen and Loeltz, 1964). The Truckee Formation is therefore of secondary importance as a source of groundwater in the study area (Hydro-Search, Inc., 1980).

The most productive aquifers in the study area are units within the older and younger alluvia. The highly variable stratigraphy of these deposits makes generalizations difficult, but the zones containing medium- to coarse-grained sands are usually capable of storing and yielding groundwater in significant amounts (Hydro-Search, Inc., 1980). Because of clay lenses and the presence of caliche in some areas, groundwater in the study area may be confined, partially confined, unconfined, or perched (SEA, 1979).

Because of the widely varying grain sizes of the three major water-bearing units and their similarities to each other, distinctions made on the basis of well logs are difficult and uncertain. Coarse alluvium, for example, may occur in all three units, and the only unique characteristic of the Truckee Formation is the presence of diatomite (Cohen and Loeltz, 1964). Cooley et al. (1971) neglected stratigraphic units and instead grouped sediments based on well logs and their characteristic hydraulic conductivities. Table 1 lists the six classes of units along with drillers' descriptions and average hydraulic conductivities.

Table 1
STRATIGRAPHIC CLASSES IN THE TRUCKEE MEADOWS
(After Cooley et al., 1971)

Class	Typical Driller's Description	Average Hydraulic Conductivity cm/s	Average Hydraulic Conductivity ft/d
1	Sand and gravel, gravel, boulders and gravel, boulders, decomposed granite. May include clay "streaks" or "breaks."	$1x10^{-2}$	40
2	Sand, loose sand with soil. May include streaks or breaks of other materials.	$4x10^{-3}$	12
3	Sand and clay, sandy clay, cemented sand. May include streaks or breaks of other materials.	$4x10^{-3}$	12
4	Gravel and clay, boulders and clay, cemented gravel, sandy clay and rocks, highly weathered rock, clay and rock. May include streaks or breaks of other materials.	$3x10^{-3}$	8
5	Clay or broken clay, hardpan, caliche, tuff. Common inclusions of streaks or breaks of other materials warrants classification as class 3 or 4, depending on inclusions.	*$5x10^{-5}$	*$1x10^{-2}$
6	Rock, granite, shale, etc.	*$5x10^{-5}$	*$1x10^{-2}$

*Estimated because of scarce data.

3.0 OCCURRENCE AND MOVEMENT OF WATER

3.1 SURFACE WATER

Steamboat Creek originates as the outlet from Little Washoe Lake and Washoe Lake at the northern edge of Washoe Valley. The two lakes are shallow, ranging up to 11 feet in depth. They are separated during dry periods by a marshy area but merge when runoff is plentiful. The bed of Washoe Lake is at 5,016 feet, the limit of outflow to Steamboat Creek is at 5,022 feet, and a small dam at the outlet of Little Washoe Lake has a spillway elevation of 5,029 feet (Rush, 1967).

Steamboat Creek is a principal tributary to the Truckee River in Nevada, joining that stream east of Sparks and just west of the canyon of the Truckee River. The creek bed has been dredged in places and has been straightened in the upper Truckee Meadows. Galena Creek, draining the southeast side of Mount Rose, is the primary natural tributary to Steamboat Creek (COE, 1972). Brown's Creek drains an area south of the Galena Creek basin and, with Galena Creek, joins Steamboat Creek in Pleasant Valley. White's Creek drains the area north of Galena Creek and flows into Steamboat Ditch, which joins Steamboat Creek in Steamboat Valley.

After traversing the upper Truckee Meadows, receiving outflow from Alexander Reservoir, and passing the Huffaker Narrows, Steamboat Creek enters a marshy area with no distinct streambed. Just downstream of this area, the creek joins with Boynton Slough and flows to the Truckee River in a broad, well-defined channel.

Because much of the area drained by Steamboat Creek in the Truckee Meadows is under agricultural use, diversions from Steamboat Creek are common, especially in the upper Truckee Meadows. Major diversions and returns were identified and gauged during this investigation.

3.2 GROUNDWATER

As described previously, most of the economically recoverable groundwater in the study area occurs in zones within the older and younger alluvia. Groundwater in these zones may be locally unconfined, confined, or perched. In some areas, particularly on the ranches south of the Huffaker Hills, groundwater occurs at or just below the land surface.

Groundwater in the study area is recharged by infiltration from irrigation ditches and streams, by subsurface flow from Steamboat Valley and the Mount Rose fan, by percolation of applied irrigation water, and, to a much lesser extent, by direct infiltration of precipitation (Cohen and Loeltz, 1964; CH2M HILL, 1983).

Although based on scanty data, Table 2 gives a rough estimate of the relative importance of each recharge source for the entire Truckee Meadows. Since these estimates were made, much agricultural land in the Truckee Meadows has been committed to urban and suburban use. The net effect of these changes has probably been to decrease the relative importance of irrigation water and to reduce the total amount of annual recharge although recharge from lawn watering in residential areas may be substantial.

Table 2
SOURCES OF GROUNDWATER RECHARGE IN THE TRUCKEE MEADOWS
(After Cohen and Loeltz, 1964)

Source of Recharge	Estimated Portion of Total Recharge
Applied irrigation water	70 percent
Ditch losses	15 percent
Truckee River infiltration	10 percent
Infiltration of other streams	2 percent
Infiltration of precipitation	Assumed to be negligible
Underflow from tributary valleys	3 percent
Estimated Total	35,000 af/y

As reflected by the high water table and upward flow gradient in much of the Truckee Meadows, the study area is largely a groundwater discharge area. Principal components of discharge are evapotranspiration and seepage to drains and streams. Smaller amounts are lost by pumping and by discharge to springs (Cohen and Loeltz, 1964). Steamboat Creek receives discharged groundwater along much of its length in the Truckee Meadows.

Water level data compiled by Cooley et al. (1971) indicate that groundwater movement in the upper Truckee Meadows is northward and toward the north-south axis of the valley. Figure 2 is a map showing groundwater flow directions in South Truckee Meadows.

The valley fill through which groundwater flows is constricted by relatively impermeable Kate Peak rocks cropping out in the Huffaker Hills. The cross section of alluvium is reduced from nearly 2 miles in width and a depth of hundreds of feet to a shallow section only approximately 1/5 mile across. This bottleneck contributes to the high water table observed just south of the Huffaker Narrows.

The northernmost portion of the study area, extending from the Huffaker Hills to the Truckee River, is essentially a separate hydrologic system from the southern portion.

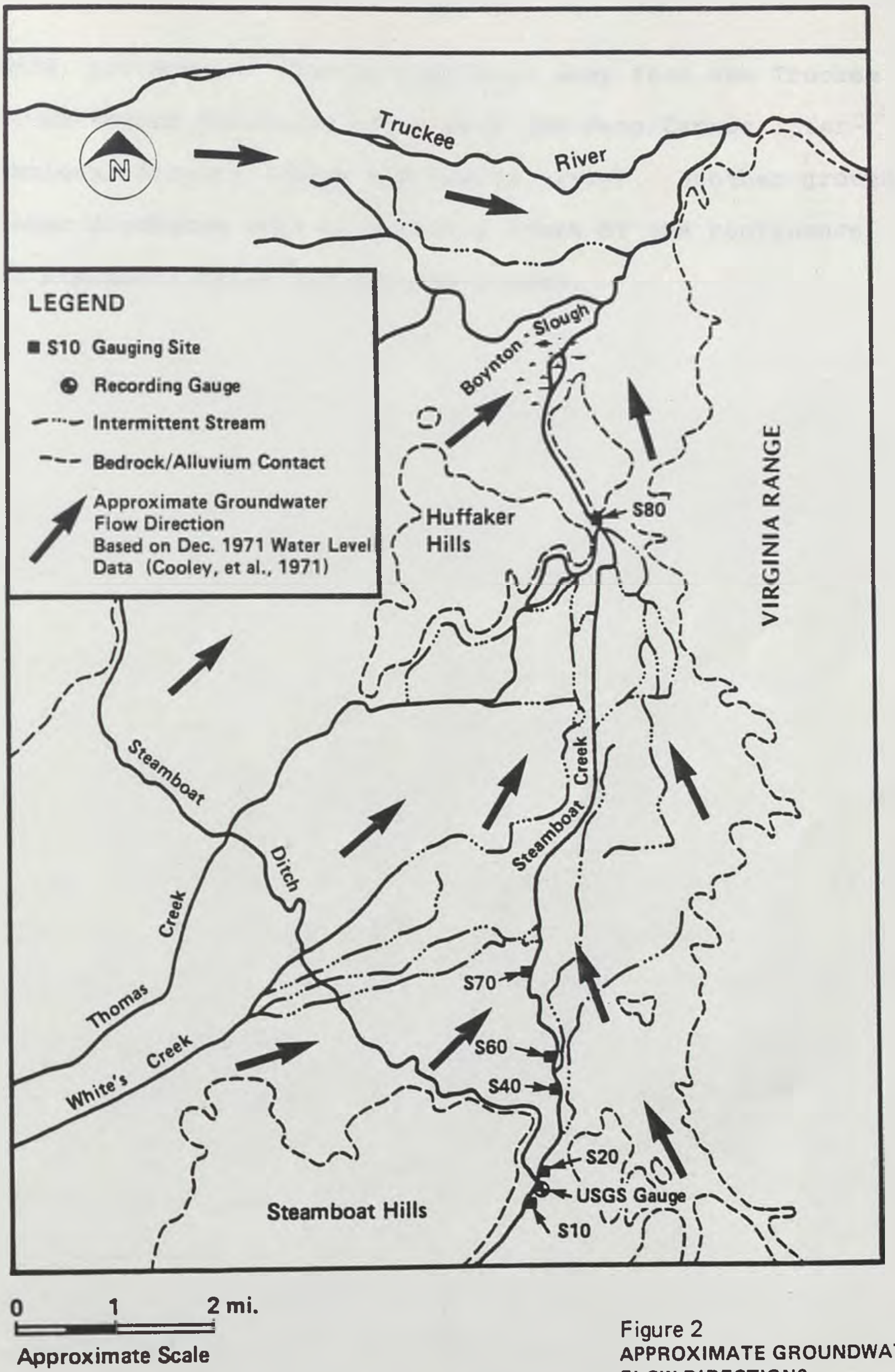

Figure 2
APPROXIMATE GROUNDWATER
FLOW DIRECTIONS
SOUTH TRUCKEE MEADOWS

Here, groundwater flow is southward away from the Truckee River toward discharge areas near the Reno/Cannon International Airport (Cohen and Loeltz, 1964). Another groundwater discharge area is directly south of the confluence of Steamboat Creek and Boynton Slough.

4.0 WATER QUALITY

4.1 SURFACE WATER QUALITY

Major sources of surface water in South Truckee Meadows are ranked below in order of generally decreasing quality.

Imported Truckee R. water	>	Surface runoff in study area	>	Nonthermal groundwater discharge	>	Hot Springs discharge

The relative influence of each of these sources depends largely upon time of year, recent precipitation events, and man's activities.

Figure 3 shows the variation of specific conductance with time for points upstream, near the middle, and at the downstream end of the study area. It is clear that during the irrigation season, when water importation is greatest, the variation in quality for all three sites is similar and the levels of dissolved solids are closest together. Between irrigation seasons, however, the values for Steamboat Creek at Big Ditch and points downstream diverge. During these periods of low flow, a greater portion of Steamboat Creek's flow consists of discharged groundwater, which is higher in dissolved solids than is

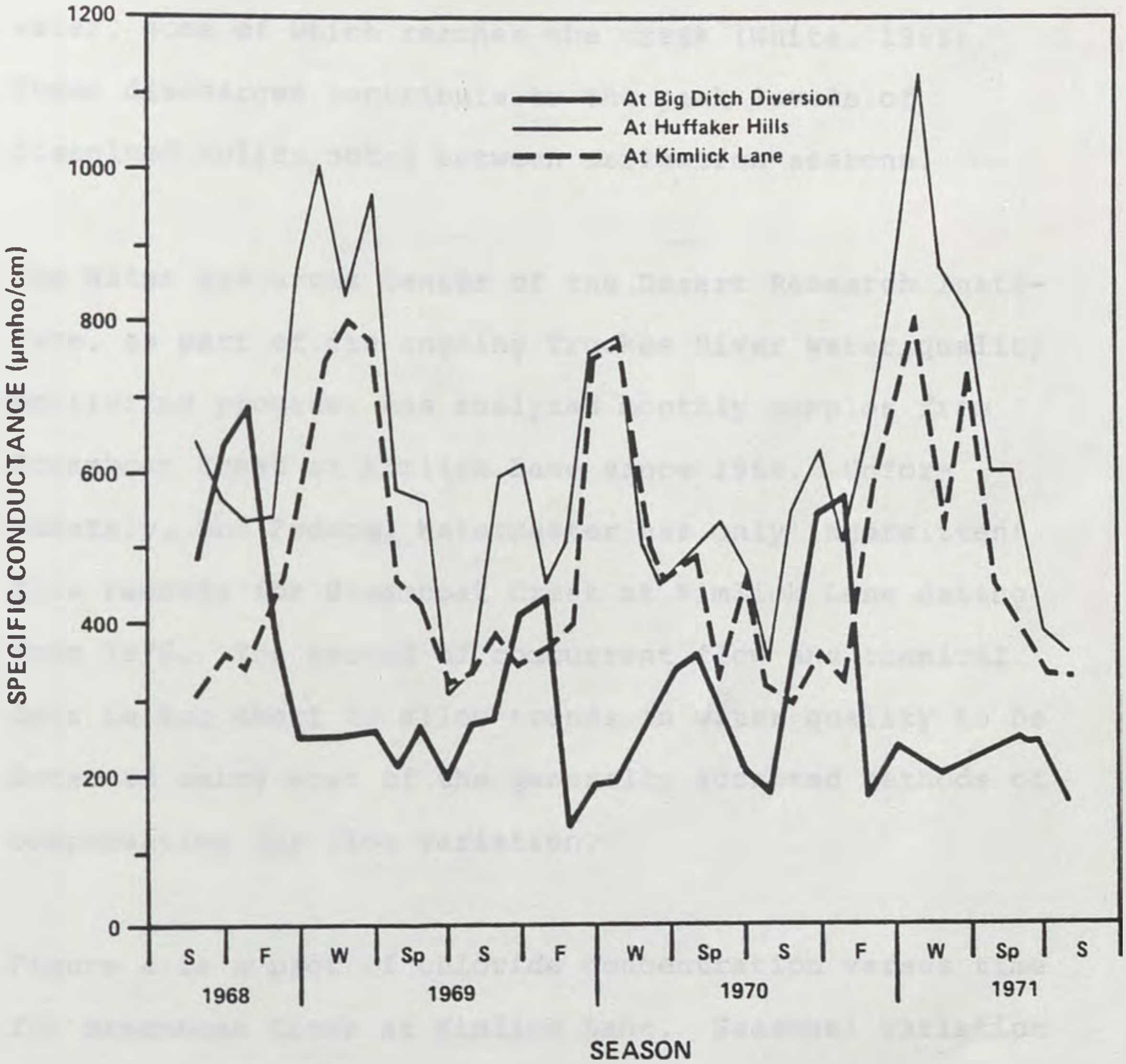

Figure 3
SPECIFIC CONDUCTANCE VARIATION FOR THREE POINTS ALONG STEAMBOAT CREEK 1968–1971

surface runoff. Additionally, Steamboat Springs, which lies between the Big Ditch and Huffaker Hills sites, discharges an estimated 1,130 gpm of poor-quality thermal water, some of which reaches the creek (White, 1969). These discharges contribute to the peak levels of dissolved solids noted between irrigation seasons.

The Water Resources Center of the Desert Research Institute, as part of its ongoing Truckee River water quality monitoring program, has analyzed monthly samples from Steamboat Creek at Kimlick Lane since 1968. Unfortunately, the Federal Watermaster has only intermittent flow records for Steamboat Creek at Kimlick Lane dating from 1976. The record of concurrent flow and chemical data is too short to allow trends in water quality to be detected using most of the generally accepted methods of compensating for flow variation.

Figure 4 is a plot of chloride concentration versus time for Steamboat Creek at Kimlick Lane. Seasonal variation in chloride concentration is clearly evident, with winter concentrations usually much higher than summer concentrations. The plot reflects the low chloride concentrations caused by abundant precipitation that occurred during early 1973. The droughts of 1977 and 1980 are also shown by sharply higher chloride levels.

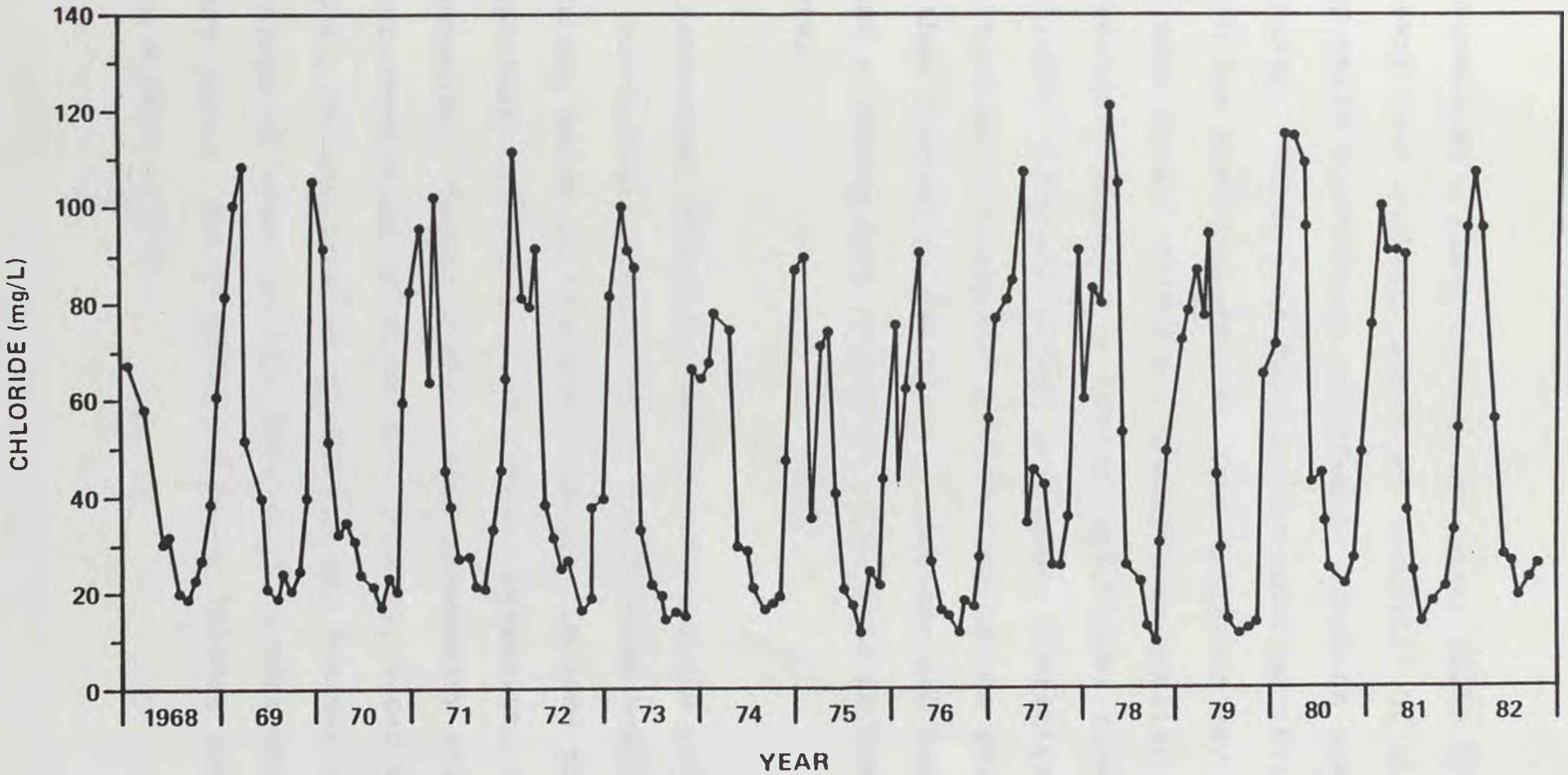

Figure 4
CHLORIDE vs. TIME FOR STEAMBOAT CREEK AT KIMLICK LANE

4.2 GROUNDWATER QUALITY

Groundwater quality varies throughout South Truckee Meadows. Waters near recharge areas are generally of the best quality while discharging groundwater exhibits somewhat poorer quality. Because of dilution by imported irrigation water with low dissolved solids, this situation may be reversed in some areas. Moreover, groundwater quality may be substantially degraded by thermal discharges from Steamboat Springs. Although mixing is common, investigators have historically classified groundwater in the study area as either thermal or nonthermal. Bateman and Scheibach (1975) used a temperature criterion of 30°C to define thermal water.

Bicarbonate, chloride, and sulfate are the principal anions in nonthermal groundwater in the Truckee Meadows. Carbonate may exist in measurable amounts in some thermal water. Important cations include sodium, potassium, calcium, and magnesium. Tables 3 and 4 list elementary statistical characteristics of major constituents, based on approximately 80 analyses of nonthermal and thermal waters. Sources of water quality data used in this study included WADS (1980), White (1968), Nehring (1980), Scheibach (1975), and Widmer (1983).

Table 3
CHEMICAL CHARACTERISTICS OF NONTHERMAL GROUNDWATER

Parameter	Mean	Range	Std. Dev.	Mean Percentage of Total Equivalents
Temp (C)	17.9	10.0-29.4	4.92	--
pH	7.78	7.0-8.8	0.47	--
S.C. (μmhos/cm)	671	236-2,320	471	--
TDS (mg/L)	564	117-2,056	403	--
HCO_3 (mg/L)	180	68-405	72	27
Cl (mg/L)	75	1.4-750	155	11
SO_4 (mg/L)	117	2.4-990	175	12
Na (mg/L)	91	4-679	112	23
K (mg/L)	10	2.1-39	9	1
Ca (mg/L)	42	3-237	40	16
Mg (mg/L)	16	2.2-80	15	10
SiO_2 (mg/L)	58	15-113	26	--

Table 4
CHEMICAL ANALYSES OF THERMAL GROUNDWATER

Parameter	Mean	Range	Std. Dev.	Mean Percentage of Total Equivalents
Temp (C)	69.9	30-145	28.7	--
pH	7.8	7.05-9.0	0.63	--
S.C. (μmhos/cm)	2,248	194-3,661	1,249	--
TDS (mg/L)	1,573	162-2,542	843	--
HCO_3 (mg/L)	249	78-461	95	16
Cl (mg/L)	387	2.6-999	376	23
SO_4 (mg/L)	145	2.3-504	128	11
Na (mg/L)	432	12-770	285	39
K (mg/L)	48	5-75	25	4
Ca (mg/L)	29	1.4-98	28	5
Mg (mg/L)	8	0.4-43	12	2
SiO_2 (mg/L)	188	4.7-317	94	--

The predominant ionic species in nonthermal water of the Truckee Meadows is bicarbonate. The range of bicarbonate concentration is fairly narrow because of the effects of carbonate equilibria (Hem, 1970). Concentration of bicarbonate is primarily dependent upon temperature, pH, the presence of a carbon dioxide source, the availability of rocks weathering to carbonate minerals, and the ambient concentrations of calcium and magnesium.

Chloride is generally the most concentrated anion in thermal waters of the area. The source of chloride in natural waters has been the subject of much discussion in geochemical literature. In many cases no source appears to account adequately for observed chloride levels in basin discharges (Feth, 1981). In the study area the source of virtually all chloride in natural water is thermal water discharged from Steamboat Springs. The minor amounts of chloride present in mountain runoff probably originated as airborne oceanic salts (Cohen and Loeltz, 1964).

The highest concentrations of sulfate in the study area are found near the valley margins. Although localized deposits of gypsum and anhydrite are present in the alluvium, the primary source of sulfate is probably hydrothermally altered rock in the surrounding mountains (Cohen and Loeltz, 1964). The Steamboat Springs system is a secondary source of sulfate in the study area. Data compiled by WRC (1971) showed that sulfate concentration decreased toward the center of the valley and generally reached a minimum near discharge areas. This decrease is likely caused by dilution with imported irrigation water.

Sodium is the principal cation in both nonthermal and thermal groundwaters in the area. Potassium has a similar distribution but is present at much lower concentrations. The primary source for both ions is the Steamboat Springs system. Sodium and potassium may also be derived from weathering of feldspars in the mountains surrounding the study area (Cohen and Loeltz, 1964). Concentrations of sodium and potassium generally decrease downgradient from Steamboat Springs.

Calcium and magnesium concentrations in South Truckee Meadows are generally low. These two ions are notable because they tend to decrease in concentration as mixing with thermal water increases. As with other constituents, the concentration of calcium and magnesium may also be reduced by dilution with imported irrigation water. Sources of calcium and magnesium include carbonates, feldspars, and amphiboles in the surrounding mountains. Local deposits of gypsum may occur in the alluvium (Cohen and Loeltz, 1964).

Data compiled by WRC (1971) suggested that an Mg:Ca ratio in groundwater greater than or equal to 0.7 generally corresponds with groundwater discharge areas in Truckee Meadows although no geochemical explanation for this situation was forwarded. This observation implies that groundwater either becomes enriched in magnesium or depleted in calcium along its flow path or that a combination of these processes occurs. No evidence of either process has yet been found in the study area; so for the present this observation remains an interesting coincidence.

5.0 STUDY METHODS

5.1 CURRENT METER MEASUREMENTS

Flow in Steamboat Creek was measured by gauging with a Gurley pygmy current meter. The procedure used is described in detail by Corbett et al. (1943). Specifically, wading measurements were made of current velocity using the "six-tenths" method.

The cross section locations gauged periodically during this study are shown in Figure 5. Geographic descriptions of gauging sites are listed in Appendix 3. A full series of measurements was typically completed in 1 day.

Corbett et al. (1943) list the criteria of an ideal cross section as icefree, perpendicular to flow, and in a stretch with uniform bed and banks. The only site regularly measured that did not at least approach this ideal was the site below the Crane Ditch diversion. Conditions here required the measurement to be made just downstream of a 90-degree bend in the bed.

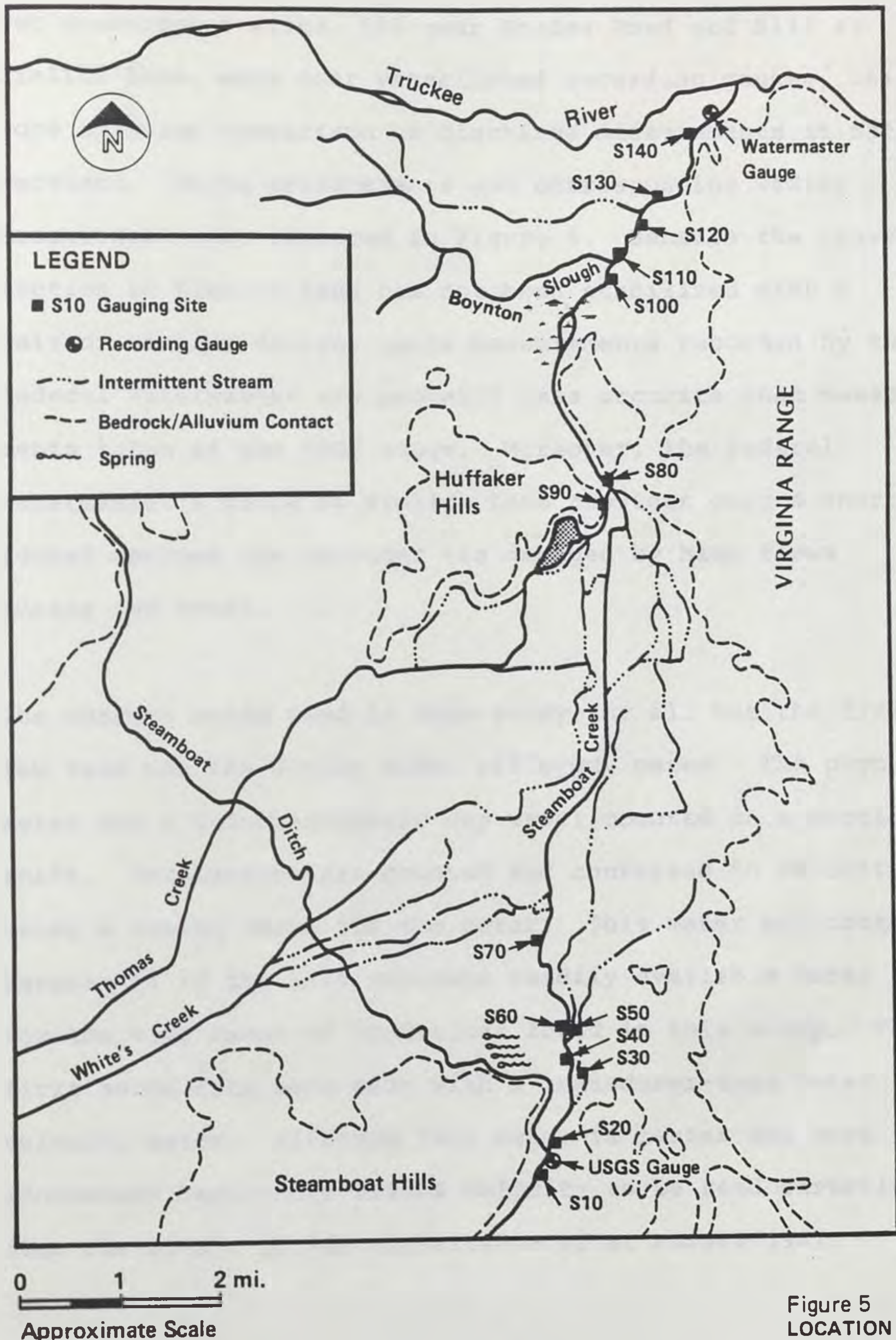

Figure 5
LOCATION OF
PERIODIC
GAUGING SITES

Two measurement sites, S10 near Rhodes Road and S140 at Kimlick Lane, were near established recording gauges, therefore allowing comparison to discharge measurements at rated sections. Gauge measurements and corresponding wading measurements are compared in Figure 6. Because the cross section at Kimlick Lane has not been stabilized with a weir or similar device, gauge measurements recorded by the Federal Watermaster are probably less accurate than measurements taken at the USGS gauge. Moreover, the Federal Watermaster's gauge at Kimlick Lane provides only a short record because the recorder was damaged by high flows during the study.

The current meter used in this study for all but the first few runs was the Gurley Model 625 pygmy meter. The pygmy meter has a 2-inch-diameter cup wheel mounted on a vertical shaft. Revolutions are counted and converted to velocity using a rating curve for the meter. This meter was chosen because it is the most accurate readily available meter for the wide range of conditions found in this study. The first three runs were made with a transducer-type water velocity meter. Although this meter is faster and more convenient because it allows velocity to be read directly from the meter, it was unavailable after August 1981.

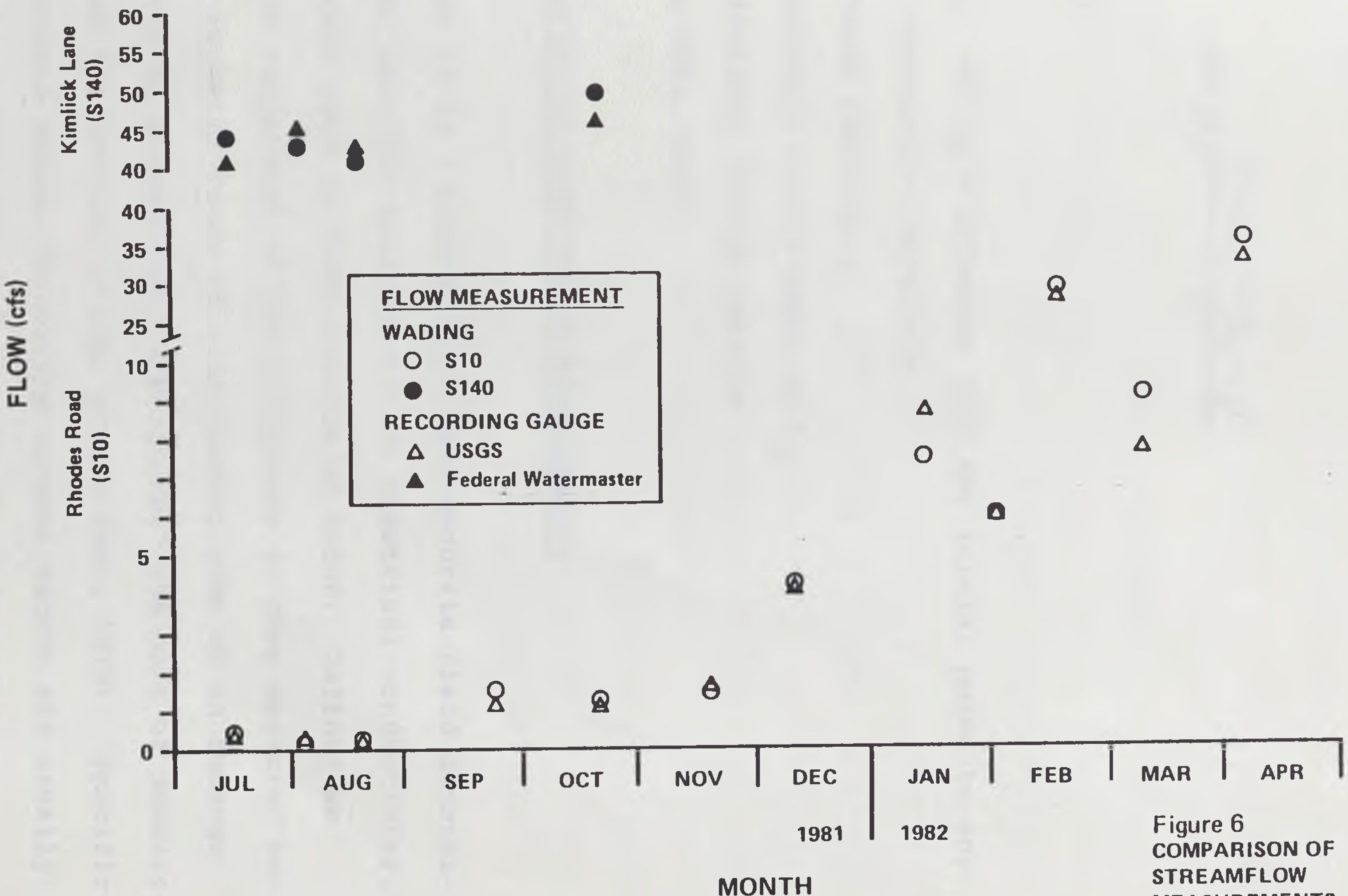

Figure 6
COMPARISON OF
STREAMFLOW
MEASUREMENTS

After a section was gauged, discharge was calculated using the following equation:

$$q=V_2D_2\frac{((L_2-L_1)+(L_3-L_2))}{2}$$

where:

L_1, L_2, and L_3 = distances from the initial point to any three consecutive verticals

D_2 = water depth at L_2

V_2 = velocity at 0.6 depth at L_2

q = discharge through section

(after USBR, 1967)

5.2 SPECIFIC CONDUCTANCE MEASUREMENTS

Because it is a simple, fast, and accurate field determination, specific conductance, or electrical conductivity, is widely used in field studies of water. Defined as "...the reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specified temperature," the unit of measurement is the inverse of ohm, or mho (Hem, 1970). Specific conductance values for dilute natural waters are usually reported as micromhos per centimeter (µmhos/cm).

In dilute solutions of simple salts, the relationship between specific conductance and ionic concentration is fairly direct (Hem, 1970). This simple relationship is somewhat misleading because conductance is actually a complex function of several variables including ionic size, ionic mobility, charge, interactions between ions, and interactions between the polar solvent and dissolved ions (Hem, 1970). As concentration increases, these effects become more pronounced and disturb the simple direct relationship between conductance and concentration. Additionally, the presence in natural waters of numerous ions with differing properties makes the relationship between specific conductance and total dissolved solids (TDS) more difficult to establish. A rough estimate of total dissolved solids may be obtained by multiplying measured conductance by a site-specific conversion factor, obtained by correlating TDS determinations with corresponding conductance measurements. This is done for South Truckee Meadows in Figure 7. The conversion factor obtained is 0.66 with a correlation coefficient of 0.989.

Just as specific conductance varies with total ionic concentration, conductance is also dependent upon temperature. For this reason, conductance measurements are usually reported at a reference temperature of 25°C. Field

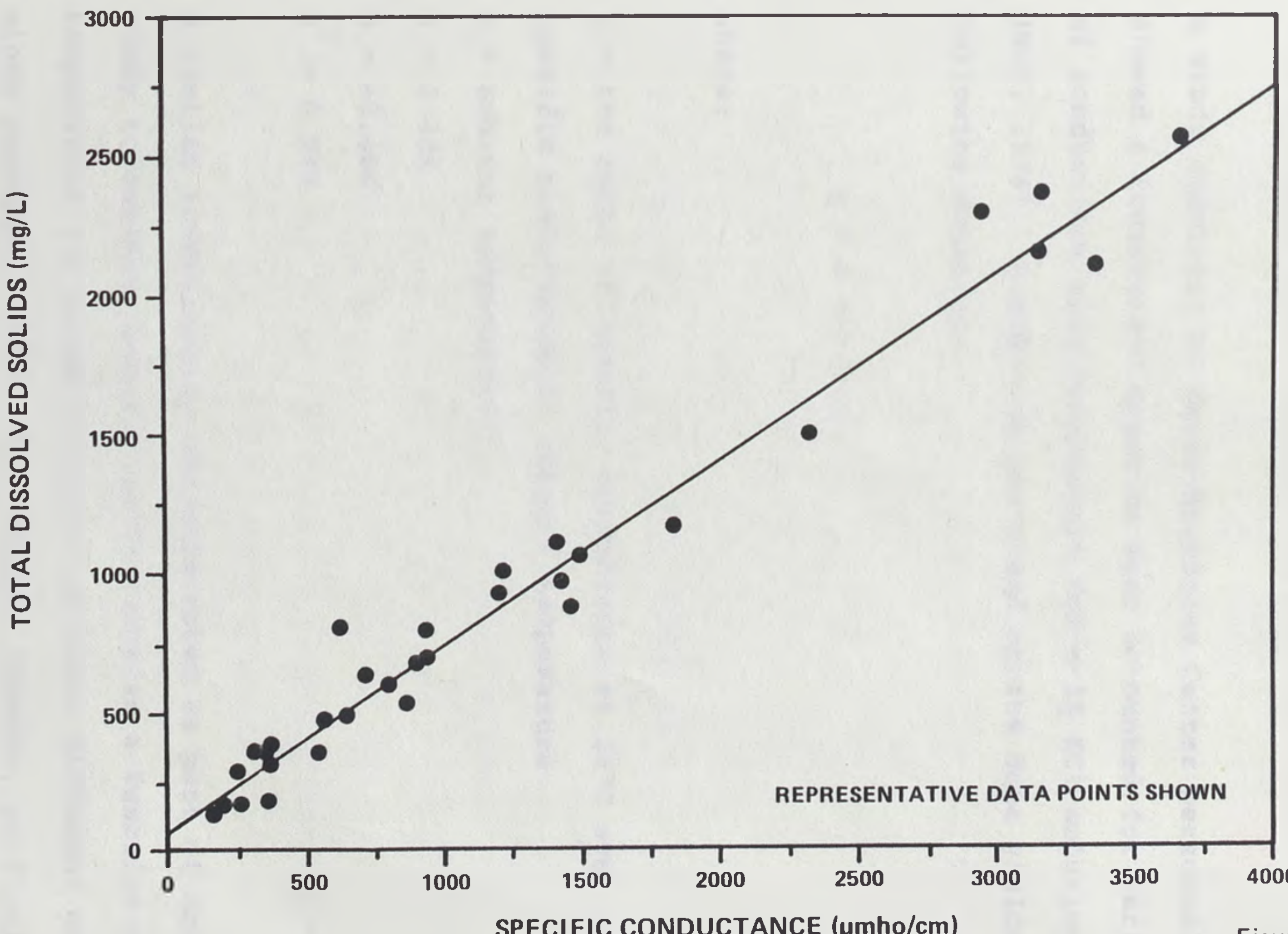

Figure 7
TDS vs. SPECIFIC CONDUCTANCE FOR SOUTH TRUCKEE MEADOWS

measurements taken at ambient temperatures must be corrected to a single temperature before meaningful comparisons can be made.

A study completed by Water Resources Center personnel showed a logarithmic equation best accounted for variation of conductance with temperature for a 1N KCl solution (WRC, 1979). Regression performed on the data yielded the following equation:

$$y = a + b\,(\ln x)$$

where:

y = the ratio of specific conductance at 25°C over the specific conductance at ambient temperature

x = ambient temperature

a = 2.488

b = -0.464

$r^2 = 0.998$

A similar investigation was undertaken as part of this study to measure specific conductance as a function of temperature for water collected at three different points along Steamboat Creek. For unknown reasons, no distinct trend was observed between conductance and temperature for any of the three samples. Specific conductance measurements for this study were therefore corrected to 25°C using the relationship obtained from WRC data described above.

Specific conductance was measured in this study using two types of meters. During the first two gauging runs a YSI Model 33 conductivity meter was used. The remainder of the conductance measurements were made with Poly-Pram multi-parameter meter Model DP-38, manufactured by the Presto-Tek Corporation.

5.3 TEMPERATURE MEASUREMENTS

Because groundwater has a fairly constant temperature throughout the year, groundwater discharge to surface water has been detected with temperature measurements during the winter when the temperature differential between groundwater and surface water is at its maximum. This method has been used primarily in lake studies. To see if this phenomenon can be correlated to groundwater discharge in Steamboat Creek, the water temperature was measured at each gauging station concurrent with the flow measurements. Temperature was measured with the Presto-Tek Model DP-38, which has a precision of one-tenth of a Celsius degree.

5.4 MINIATURE PIEZOMETERS

To calculate the groundwater contribution to streamflow using discharge measurements at several points along a stream, it is necessary to know the location and flow of major diversions and returns. This can be a difficult task in irrigated areas where the surface flow system is complex and may be inadequately mapped. It is theoretically much simpler to measure head differences and hydraulic conductivity in the streambed, therefore allowing groundwater discharge to be calculated directly. This task was completed using miniature piezometers as described by Lee and Cherry (1978).

Miniature piezometers differ from piezometers in that they are smaller and are manually installed. The piezometer itself consists of a 1/8-inch-internal-diameter plastic tube approximately 5-1/2 feet in length. The last 2 inches of the piezometer are perforated and are wrapped with a fine nylon mesh netting to screen out sediment.

The piezometer is installed by driving a 5/8-inch-internal-diameter steel pipe vertically into the stream bed (Figure 8). To prevent sediment from entering through the bottom of the pipe and to keep the hammer from flattening the top of the pipe and sealing its opening, the ends of

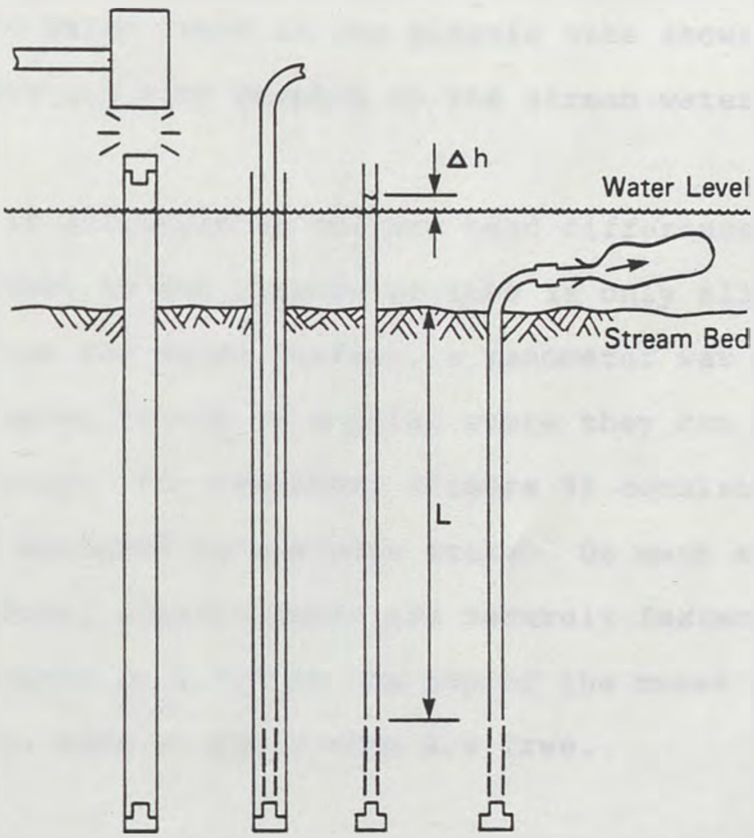

Figure 8
MINIATURE PIEZOMETER INSTALLATION

the pipe are loosely fitted with 7/16-inch lag bolts. After the steel pipe is driven to the desired depth, usually about 3 feet, the top lag bolt is removed and the piezometer inserted. While the piezometer is held in place, the steel pipe is slowly withdrawn. The bottom bolt remains in the sediment near the piezometer tip. After equilibrium is reached, the water level in the plastic tube shows the head differential with respect to the stream water.

Because it is difficult to measure head differences when the water level in the piezometer tube is only slightly above or below the water surface, a manometer was used to bring both water levels to a point where they can be accurately measured. The manometer (Figure 9) consists of a meter stick attached to a wooden stake. On each edge of the meter stick, plastic tubes are securely fastened. The tubes are joined by a "Y" at the top of the meter stick while the two ends at the bottom are free.

The manometer is installed vertically next to the piezometer, and the bottom ends of the tubes are allowed to dangle in the stream water. A rubber suction bulb attached at the top of the "Y" is squeezed to blow water out of the tubes, then is released slowly, allowing the water in the tubes to rise to a static level. After ensuring both tubes

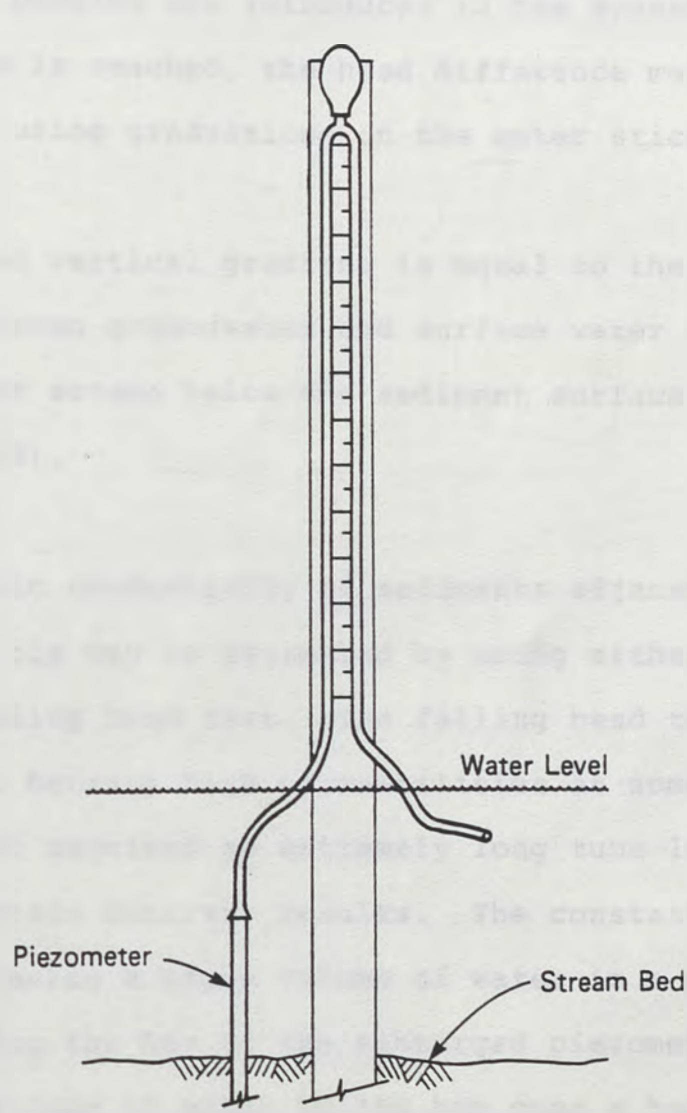

Figure 9
MANOMETER FOR MINIATURE PIEZOMETERS

are free of air bubbles, one tube is connected to the piezometer tube, which has been cut off below the stream water level. It is important that the tubes remain submerged during the connection so that suction is maintained and no air bubbles are introduced to the system. After equilibrium is reached, the head difference may be easily determined using graduations on the meter stick.

The measured vertical gradient is equal to the head difference between groundwater and surface water over the depth of the screen below the sediment surface (Lee and Cherry, 1978).

The hydraulic conductivity of sediments adjacent to the piezometer tip may be estimated by using either a constant head or falling head test. The falling head test was impractical because high permeabilities at some locations in the creek required an extremely long tube length in order to obtain accurate results. The constant head test involves placing a known volume of water in a plastic bag and attaching the bag to the submerged piezometer. The change in volume of water in the bag over a known time interval is measured and recorded. This test is known as a constant head test because the head in the bag remains constant and equal to the level of the stream for the duration of the test (Lee and Cherry, 1978).

Hydraulic conductivity is calculated using equations developed by Hvorslev (1951) for several different types of piezometers. For a piezometer with a screened interval and an open bottom, the following equation may be used with data from a constant head test (after Hvorslev, 1951):

$$K = \frac{q \ln \left(\frac{L}{D} + \left(1 + \frac{L}{D}^{2} \right)^{\frac{1}{2}} \right)}{2\pi L H}$$

where K = hydraulic conductivity (cm/s)

q = volume collected over time interval (cm^3/s)

L = length of screened section (cm)

D = diameter of piezometer tube (cm)

H = head difference between groundwater and surface water (cm)

5.5 WATER QUALITY SAMPLING

Though relatively plentiful, waters in South Truckee Meadows are of variable quality. As a result of contributions from Steamboat Springs, runoff from the altered rocks of the Virginia Range, adsorption/desorption processes in the alluvial valley fill, and contributions from human activity, some constituents may occur in concentrations that will render the water unsuitable for certain uses. Arsenic and boron are of particular concern in the study area.

In humans, acute arsenic poisoning may lead to degeneration of the gastrointestinal tract, liver, kidneys, and bone marrow (USEPA, 1980). Symptoms of low-level chronic exposure are fatigue and loss of energy. Although a clear cause-and-effect relationship has not been established, chronic arsenic exposure from drinking water supplies has been correlated with an increased incidence of skin cancer in Taiwan, Argentina, and Chile (USEPA, 1980). The USEPA (1976) suggested arsenic criteria of 50 micrograms per liter (μg/L) for domestic water supplies and 100 per liter (μg/L) for irrigation water. In response to Section 304(a)(1) of the Clean Water Act of 1977 (P.L. 95-217), the USEPA (1980) modified the criteria in terms of exposure risk. These criteria are summarized in Table 5.

Table 5
WATER QUALITY CRITERIA FOR ARSENIC
(After USEPA, 1980)

Risk Level	Criterion (μg/L)
10^{-7}	0.22
10^{-6}	2.2
10^{-5}	22

Daily exposure equals 2 liters of drinking water.

Boron is not known to be required by humans and is relatively nontoxic to animal life (USEPA, 1976). It is considered a micronutrient for plants, yet elevated levels of boron in water may be harmful to some plants (Buckman and Brady, 1969). The USEPA (1976) has set a criterion of 750 µg/L for long-term irrigation on sensitive crops. Because boron is not one of the 65 toxic pollutants listed under Section 307(a)(1) of the Clean Water Act, this criterion has not been revised to date (USEPA, 1980).

Arsenic is a common, though minor, constituent in a large variety of rocks. Its concentration ranges up to 5.9 ppm for extrusive igneous rocks (Onishi and Sandell, 1955). Elevated levels of arsenic are often associated with thermal water, and because of arsenic's affinity for sulfur as the sulfide ion, hot spring deposits will often concentrate arsenic (Onishi and Sandell, 1955, and Ferguson and Gavis, 1972).

Boron is one of the most mobile elements in the earth's crust. As with arsenic, boron is found in extrusive igneous rocks and hot spring deposits. Additionally, boron has also been associated with lake deposits in arid regions (Watanabe, 1975).

Because extrusive igneous rocks, hot springs, hot spring deposits, and lake deposits are all found in the study area, the source of boron and arsenic in waters of the area is not immediately obvious. In an attempt to identify the most likely sources, a limited sampling program was completed.

Specific conductance measurements indicate three points of rapid chemical change along Steamboat Creek. These points are just downstream of the confluence with Steamboat Ditch (S20), at the Crane Ditch diversion (S60), and at the State Route 341 (Geiger Grade) bridge (S70). Samples taken at these points, along with samples taken at the USGS gauge below Rhodes Road (S10) and at the Short Lane bridge (S80), were analyzed for major constituents, boron, and arsenic. Additionally, three samples taken roughly midway between these sampling points were analyzed solely for boron and arsenic (S40, S60A, and S70A). Sampling locations are shown in Figure 10.

After laboratory results on these samples were obtained, boron and arsenic loading per unit stream length was calculated. These results are summarized in Table 6. The S40-S60 and S60A-S70 stretches were similar in boron increase per unit stream length, and the S40-S60 stretch showed the highest rate of arsenic loading.

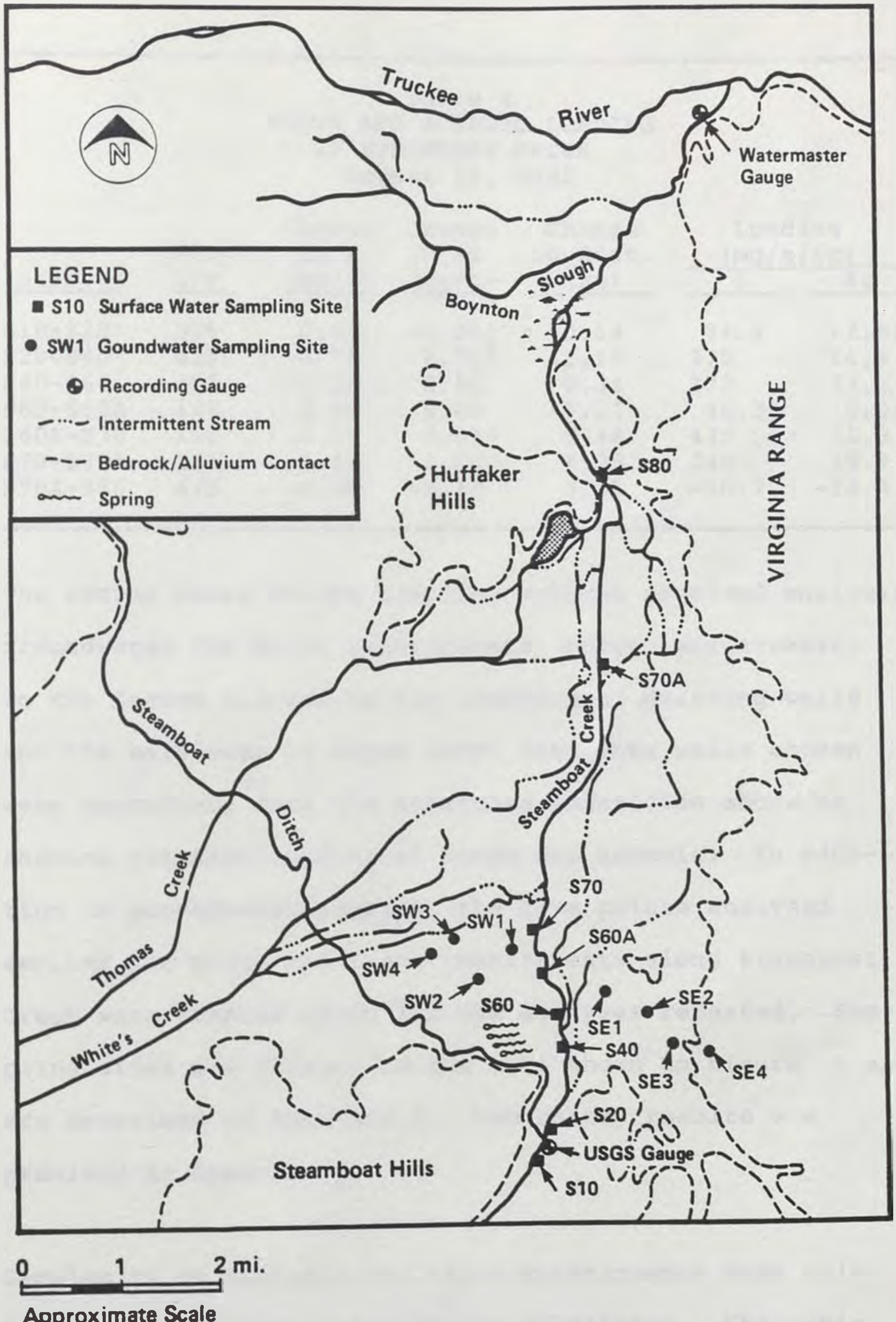

Figure 10
WATER SAMPLING SITES

Table 6
BOREON AND ARSENIC LOADING
IN STEAMBOAT CREEK
August 25, 1982

Interval	Flow l/s	Change in B (mg/L)	Change in As (mg/L)	Change in Dist. (km)	Loading (mg/s/km) B	As
S10-S20	395	0.03	-0.001	0.14	84.6	-2.82
S20-S40	425	0.75	0.046	1.16	275	16.9
S40-S60	395	0.32	0.02	0.34	372	23.2
S60-S60A	140	0.40	0.00	1.21	46.3	0.00
S60A-S70	190	1.10	0.030	0.48	435	11.9
S70-S70A	340	3.10	0.14	4.35	242	10.9
S70A-S80	425	-0.40	-0.13	3.35	-50.7	-16.5

The second phase of the sampling program involved analyzing groundwater for major constituents, boron, and arsenic. To the degree allowed by the location of existing wells and the existence of water level data, the wells chosen were upgradient from the stretches identified above as showing greatest loading of boron and arsenic. In addition to groundwater samples, the five points analyzed earlier for major and trace constituents along Steamboat Creek were sampled again and the analyses repeated. Sampling sites are located in the area shown in Figure 10 and are described in Appendix 3. Laboratory results are provided in Appendix 2.

Samples to be analyzed for major constituents were collected in a 4-liter polyethylene cubitainer. The cubitainer was rinsed with sample water, filled with sample water, squeezed to expel remaining air, tightly sealed with a paper lined plastic cap, and chilled to 4°C. The boron and arsenic samples were taken in a 1-liter polyethylene bottle. Approximately 500 ml of each of these samples were subsequently filtered through a 0.40-micron polycarbonate filter and divided into two parts. The 200 ml to be analyzed for arsenic were acidified with HNO_3. These samples were stored until analysis in 250-ml plastic bottles with paper-lined caps. When wells were sampled, water was run to waste until the pump engaged and the temperature of discharging water stabilized (Scalf et al., 1981).

Laboratory results of water samples collected during this study are provided in Appendix 2.

6.0 DISCUSSION OF RESULTS

6.1 GROUNDWATER DISCHARGE TO STEAMBOAT CREEK

Groundwater discharge to Steamboat Creek was determined indirectly by measuring the flow variation along the creek. An increase in streamflow in a downstream direction indicated that the creek was receiving discharged groundwater. Results of flow measurements taken along Steamboat Creek from July 1981 to April 1982 are presented in Appendix 1. Flow variation is summarized in Table 7.

It is readily apparent that calculated flow variation changed throughout the period of measurement. In general, the changes do not seem to follow any seasonal pattern. Moreover, the period of record is too short for any seasonal pattern to be confirmed. For these reasons, a simple mean of the calculated rates for each interval will be used in the following discussion.

Some values listed in Table 7 differ substantially from other determinations for the same interval. For example, the October 20, 1981, value for the interval S80-S100 is 12.0 cfs. The next highest value for the same interval is 1.98 cfs, and the median for this interval is 1.72 cfs.

Table 7
SUMMARY OF FLOW VARIATION ALONG STEAMBOAT CREEK
(Flow change in cfs across the interval)

Date	S10-S40	S40-S60	S20-S60	S60-S70	S70-S80	S80-S100	S110-S120	S130-S140
7/16/81	--	--	-6.50	0.15	--	--	-0.66	3.66
8/3/81	--	--	1.10	0.08	--	--	1.29	0.11
8/18/81	--	--	1.32	0.84	--	--	-1.75	4.20
9/24/81	--	--	1.20	0.56	14.7	1.80	-2.29	--
10/20/81	--	--	0.60	0.28	9.62	12.0	-2.10	0.87
11/19/81	--	--	0.35	0.97	17.1	1.39	-5.23	1.67
12/10/81	0.82	0.41	--	0.43	13.9	1.30	-2.72	5.36
1/14/82	0.70	0.47	--	1.16	13.4	1.72	-4.69	--
2/2/81	0.88	0.18	--	0.64	11.9	1.83	-2.50	2.62
2/18/82	1.00	2.90	--	0.30	27.3	1.98	-9.10	--
3/9/82	0.68	-0.87	--	0.69	12.9	1.33	-0.15	1.16
4/6/82	0.30	1.30	--	1.00	15.1	-9.04	0.87	3.60

Because the surface flow system of Steamboat Creek includes numerous small, intermittent, and frequently unmapped diversions or returns, it is likely that anomolies such as these are due to unaccounted-for diversions or returns rather than changes in the rate of groundwater influx. It was therefore necessary at times to disregard unusually high or low values when calculating the mean groundwater inflow for an interval.

The intervals S10-S40 and S40-S60 were measured in the fall and winter when Steamboat Ditch was not flowing. The mean groundwater discharge rates for these intervals was calculated to be about 0.73 cfs for S10-S40, and 0.73 cfs for S40-S60. The distance between S10-S40 is approximately 0.82 mile, resulting in a seepage rate of approximately 0.89 cfs per mile over the interval. The distance of approximately 0.21 mile between S40 and S60 gives a rate of 3.5 cfs per mile. Subsurface discharge from Steamboat Springs probably contributed to the high rate of influx to the creek measured between S40 and S60. Total groundwater inflow over S10-S60 averaged to 1.46 cfs over 1.03 miles or 1.4 cfs per mile.

This rate should be fairly close to the estimated rate for the interval S20-S60 because the two intervals cover almost exactly the same stretch of the creek. Measured during the summer when Steamboat Ditch was carrying diverted Truckee River water, the rate for S20-S60 was determined to be 0.91 cfs over 0.91 miles, or approximately 1.0 cfs per mile. This is somewhat less than the estimated 1.4 cfs per mile for S10-S60. A possible reason for the discrepancy in the average groundwater discharge over S10-S60 and S20-S60 is that the calculated flow difference over S20-S60 and S40-S60 requires adding flows in two diversion ditches together with leakage from the Crane Ditch diversion structure, potentially compounding any errors in measurement. Seasonal variation could also contribute to the difference in calculated groundwater inflow.

It should be mentioned that the calculated groundwater discharge over S20-S60 on July 16, 1981, was disregarded in computing a mean for this interval. The large negative number differs substantially from the other measurements for this interval. The flow loss across the interval on this date was probably due to an unnoticed diversion between the two measurement stations.

The interval S60-S70 required measuring some of the lowest flows encountered during this study. Turbulence was fairly pronounced at S70, particularly as flows increased from spring runoff. Nevertheless, determinations of groundwater discharge to this stretch were fairly consistent throughout the study, averaging 0.59 cfs over 1.06 miles for a rate of approximately 0.56 cfs per mile.

Because of difficult access, the interval S70-S80 was the longest continuous interval in the study. Because of its length and complexity, this interval was subdivided and gauged in the fall of 1982. The results of this gauging run are discussed later in this section.

Estimates of groundwater discharge over S70-S80 are not listed for the first three gauging runs because a north-flowing ditch on the Bella Vista Ranch south of Short Lane was mistaken for Steamboat Creek at the outset of this study. The record of estimates for this interval therefore begins in September 1981. It should also be mentioned that flows at S80 used in calculating flow increases between S70 and S80 are derived, rather than directly measured, flows. This was necessary because flows measured at S80 included S90, outflows from Alexander Reservoir. The flows at S80 used to calculate flow differences over S70-S80 are therefore the differences of S80 and S90, equal to the flow in Steamboat Creek upstream of the confluence with Alexander Lake ditch.

Over the course of the regular series of gauging runs, the flow increase in Steamboat Creek over the interval S70-S80 ranged from a high of 27.3 cfs to a low of 9.62 cfs and averaged 15.1 cfs. If this increase is assumed to be entirely due to groundwater discharge to the creek, the rate over 4.83 miles is 3.1 cfs per mile.

The fairly high rate of groundwater influx to Steamboat Creek measured between S70 and S80 is probably related to a bottleneck effect caused by the Huffaker Narrows. As shallow groundwater flows northward across the South Truckee Meadows, it is forced through a comparatively small aquifer cross section at the Huffaker Narrows. This causes high water table conditions and apparently increases the rate of groundwater discharge to Steamboat Creek.

In an attempt to more accurately measure groundwater inflow to Steamboat Creek over S70-S80, more detailed measurements were made along this interval in October 1982. The results of these measurements are listed in Table 8. Figure 11 shows the locations of gauging sites between S70 and S80.

Even though every attempt was made during this gauging run to account for all surface inflows and outflows, in some areas the marshy character of lands adjacent to Steamboat Creek made the task difficult. The intervals S73-S74,

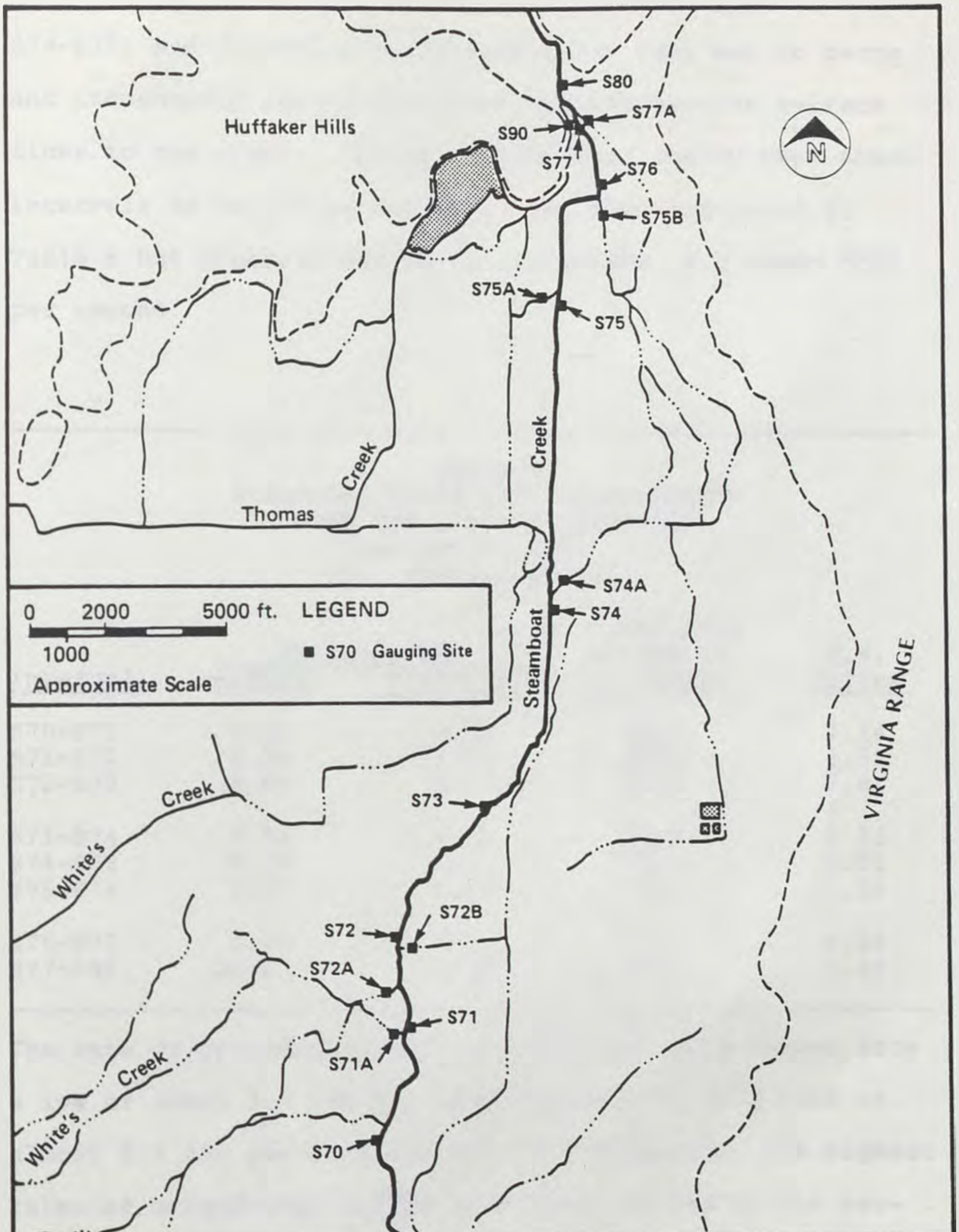

Figure 11
STREAM GAUGING SITES BETWEEN S.R. 341 AND SHORT LANE

S74-S75, and S75-S76 were in particular very wet in parts and undoubtedly contributed some unaccounted-for surface flows to the creek. The net groundwater inflow over these intervals is therefore somewhat less than indicated in Table 8 but probably only by a few tenths of a cubic foot per second.

Table 8
STEAMBOAT CREEK FLOW MEASUREMENTS
OVER THE S70-S80 INTERVAL
October 19, 1983
(All values in cfs)

Interval	Surface Flow Return	Surface Flow Diversion	Creek Flow at End of Interval	G.W. Influx
S70-S71	0.51	0.00	18.8	0.34
S71-S72	0.26	1.04	18.6	0.52
S72-S73	0.00	0.00	20.5	1.81
S73-S74	0.00	0.00	22.9	2.52
S74-S75	0.00	11.6	13.3	2.01
S75-S76	2.97	0.00	17.5	1.29
S76-S77	0.00	0.00	18.2	0.64
S77-S80	22.0	0.00	38.7	-1.46

The rate of groundwater inflow in cfs per mile ranged from a low of about 0.7 cfs per mile for S70-S71 to a high of almost 2.7 cfs per mile for S73-74. Generally, the highest rates of groundwater inflow were found in the middle section of SR 341--Short Lane stretch, or more precisely between the stations labeled S72 and S76. Overall, groundwater seepage to Steamboat Creek in October 1982 averaged about 1.9 cfs per mile through the S70-S80 interval.

Of the 12.1 cfs flow increase across S70-S80 that was measured in October 1982, approximately 3/4, or 9.13 cfs, can be attributed to groundwater discharge to the streambed. The remaining 3 cfs were due to surface water inflow from return ditches and marshy areas. It is possible that the 3/4 ratio may vary somewhat throughout the year because surface water inflows would increase during the summer irrigation season and decrease during the winter. Nevertheless, if 3/4 is used as an estimate of the average ratio of groundwater influx to total flow increase across the S70-S80 interval, the average flow increase of 15.1 cfs would consist of approximately 11 cfs of discharged groundwater, for a rate of 2.4 cfs per mile.

Across the S80-S100 interval Steamboat Creek changes from a narrow, at times swift-flowing stream with a width ranging up to about 16 feet, to a wide, shallow, relatively sluggish stream with a width exceeding 30 feet. S80-S100 also includes a broad, marshy area located near the northeast corner of Section 28, T19N R20E. Because of distributaries and the absence of a distinct streambed in parts of this marshy area, as well as difficult access to other portions of this interval, S80-S100 is a relatively long 2.7 miles in length.

Because of the error described earlier concerning the location of Steamboat Creek at Short Lane, the period of record for the interval S80-S100 begins in September 1981. It should be noted that the values of 12.0 cfs for October 1981 and -9.04 cfs for April 1982 were disregarded when calculating the mean groundwater influx for this interval. While groundwater discharge rates can be expected to vary within certain limits, it is unlikely that they could vary to the degree suggested by these measurements. Variation is more likely due to overlooked returns or diversions. The average of the seven remaining determinations of groundwater discharge to this interval is 1.6 cfs over 2.7 miles, for a rate of about 0.6 cfs per mile.

The only stream segment in the South Truckee Meadows where Steamboat Creek regularly decreased in flow was the S110 to S120 interval. The flow change across this interval was positive on two occasions but averaged a negative 2.4 cfs.

An examination of specific conductance data at S110 and S120 (Appendix 1) indicates that specific conductance generally decreased as flow decreased. Where the flow between S110 and S120 increased or stayed roughly constant, specific conductance changed very little. This suggests that the creek was not simply losing water, because a simple flow decrease would have no effect on specific conductance. Instead, the creek was apparently receiving an influx of water with generally lower specific conductance as well as losing a greater amount of water somewhere else between S110 and S120.

Although no surface diversion was identified between S110 and S120, it is most likely that the loss of water was caused by an overlooked diversion or possibly by shallow wells pumping near the creek. It is less likely that the flow decrease was due to the creek's losing flow to groundwater because the creek receives discharged groundwater everywhere else in the Truckee Meadows and because the S110 to S120 interval is adjacent to a groundwater discharge area (T19N, R20E, Sec 15) identified by Cohen and Loeltz (1964).

A possible explanation for the observed results is that Steamboat Creek received a minor amount of discharged groundwater across S110 to S120. At the same time, several cubic feet per second were withdrawn by pumping nearby wells or by surface diversions, causing a net decrease in flow across the interval.

The final stretch of Steamboat Creek, S130-S140, involved measuring some of the highest flows encountered during this study. Because of high flows, great stream depth, and a rocky, uneven streambed, measurements at S140 are probably the least accurate of all the sites. Unfortunately, Federal Watermaster records for this site are intermittent, making comparison difficult (Figure 6). Wading measurements indicate that flow in Steamboat Creek increased an average of about 2.6 cfs over 0.92 mile, for a rate of approximately 2.8 cfs per mile.

Estimates of the degree of error in current meter flow measurements typically range from 5 percent to 10 percent (Corbett et al., 1943). For purposes of evaluation, an error of 5 percent is assumed for flow measurements made during this study.

Table 9 lists the average flow change for each interval that had a consistent flow increase during the study. The predominantly negative values in the second column indicate that the flow change between adjacent stations was generally less than plus or minus 5 percent.

In the ideal sense, this indicates that the current meter gauging method was usually not sensitive enough to detect a flow increase in the downstream direction. In the real sense, the relative consistency of flow increases measured between many sites suggests that increases are actual and not due solely to random error. Moreover, because the variable of interest is calculated from a flow difference, the absolute magnitudes of flow are not of prime importance. Nonrandom error--such as consistently overestimating all flows by the same amount--would not affect the magnitude of the differences.

Table 9
AVERAGE FLOW CHANGE ASSUMING 5 PERCENT ERROR

Interval	Average Measured Flow Change (cfs)	Average Minimum Flow Change[a] (cfs)	Average Maximum Flow Change[b] (cfs)
S10-S40	0.73	-0.84	2.30
S40-S60	0.73	-0.91	2.37
S20-S60	0.91	-0.74	2.56
S60-S70	0.59	-0.24	1.43
S70-S80	15.1	13.2	17.0
S80-S100	1.61	-1.59	4.81
S130-S140	2.6	-1.9	7.15

[a]Difference between downstream station flow less 5 percent and the upstream station flow plus 5 percent.

[b]Difference between downstream station flow plus 5 percent and the upstream station flow less 5 percent.

Figure 12 is a plot of flow at each station for measurements taken on February 2, 1982. The plot indicates that, although the 5 percent error spread at a specific location may overlap with the error spread at an adjacent location,

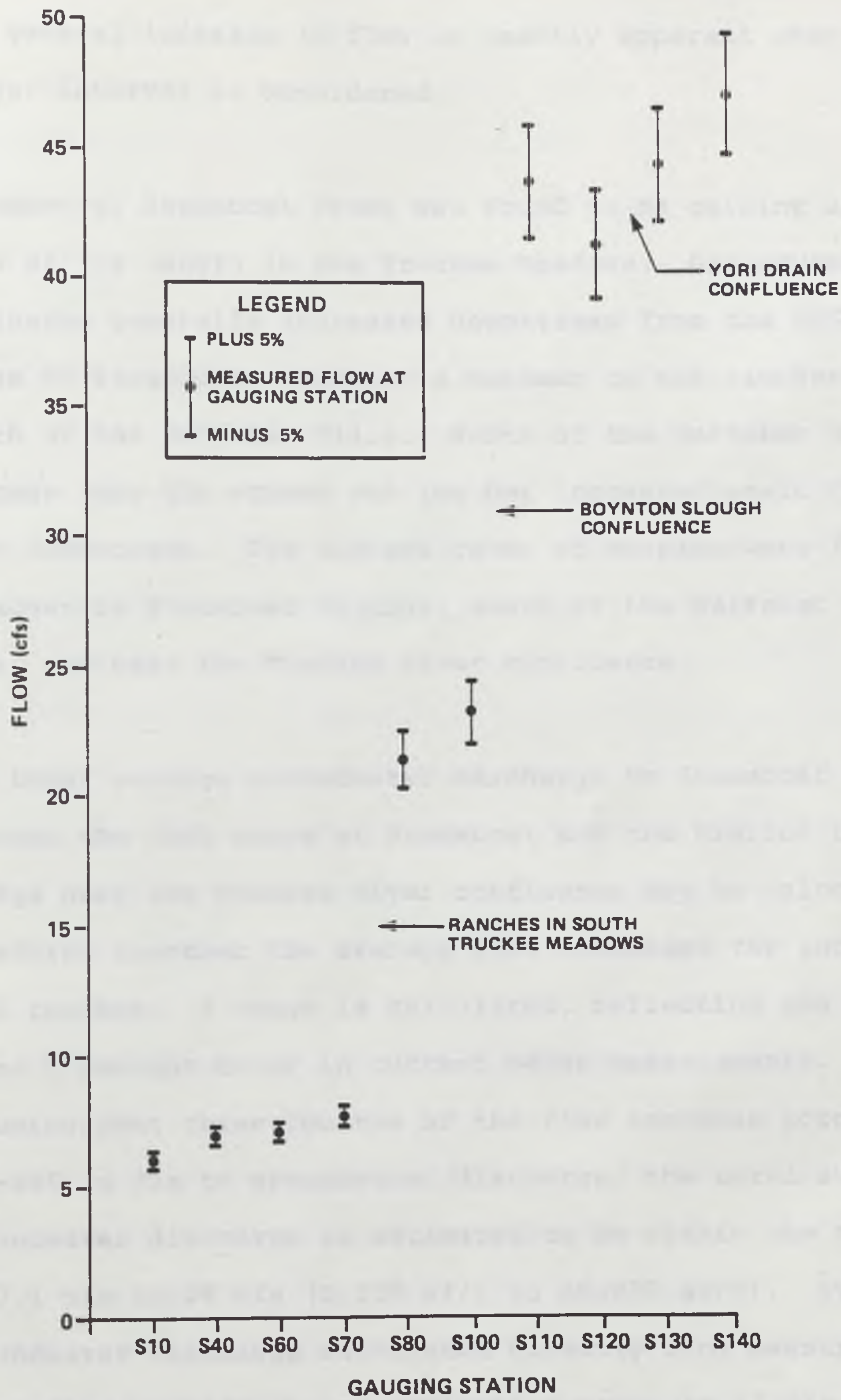

Figure 12
FLOW IN STEAMBOAT CREEK
FEBRUARY 2, 1982

the general increase in flow is readily apparent when a longer interval is considered.

In summary, Steamboat Creek was found to be gaining along much of its length in the Truckee Meadows. Groundwater discharge generally increased downstream from the USGS gauge at Steamboat, reaching a maximum on the ranches just south of the Huffaker Hills. North of the Huffaker Hills, seepage into the stream was low but increased again farther downstream. The highest rates of seepage were found adjacent to Steamboat Springs, south of the Huffaker Narrows, and near the Truckee River confluence.

The total average groundwater discharge to Steamboat Creek between the USGS gauge at Steamboat and the Kimlick Lane bridge near the Truckee River confluence may be calculated by adding together the average flow increases for individual reaches. A range is calculated, reflecting the estimated 5 percent error in current meter measurements. Assuming that three-fourths of the flow increase across S70-S80 is due to groundwater discharge, the total average groundwater discharge is estimated to be within the range of 7.1 cfs to 28 cfs (5,100 af/y to 20,000 af/y). Average groundwater discharge calculated directly from measured streamflow variations and neglecting error is 17 cfs

(12,500 af/y). Cohen and Loeltz (1964) reported ground-water discharge to Steamboat Creek between the USGS gauge and Huffaker Hills as 14 cfs in December 1957. This is within the calculated range of 10.6 cfs to 16 cfs and close to the mean of 13 cfs estimated during this study.

The absence of any evidence of seasonal trends in ground-water inflow was somewhat disappointing, yet hardly surprising, considering the brief period of record. Ground-water seepage would be expected to generally increase during the summer, lagging the irrigation season somewhat, only to decrease again after irrigation ceases in the fall. Conversely, transpiration by riparian vegetation peaks during the summer and decreases in the fall and winter. Perhaps the opposition of these two processes reduced seasonal fluctuations to a level that the current meter measurements were not sensitive enough to detect.

6.2 SEEPAGE MEASUREMENTS WITH MINIATURE PIEZOMETERS

According to Lee and Cherry (1978), miniature piezometers in streams perform best when water velocity is less than about 0.7 foot per second, when water depth is less than 2 feet, and where the streambed is composed of firm sand with very little gravel or cobble. With these criteria in mind, the sites listed in Table 10 were chosen as most appropriate.

Table 10
LOCATION OF MINIATURE PIEZOMETERS

Piezometer Number	Location Description
P1	15 y downstream of confluence with Steamboat Ditch (S20)
P2	100 y upstream of Crane Ditch diversion structure (S50)
P3	20 y upstream of Crane Ditch diversion structure (S50)
P4	25 y downstream of Short Lane (S80)
P5	150 y upstream of confluence with Boynton Slough (S100)
P6	50 y upstream of confluence with Boynton Slough (S100)

The most restrictive criteria were streambed composition and flow velocity. Where the bed is generally sandy, often the case in the upper reaches of the creek, flow velocities are typically fairly high. As flow velocity decreases farther downstream, finer grained sediments are deposited and the bed becomes silty or muddy.

Piezometers P1 through P4 were located in stretches that conform fairly well to the criteria. Piezometers P5 and P6, though located as well as possible, were installed in stretches where the streambed was fairly silty. Piezometers were not installed around State Route 341 because flow velocity was high and the bed rocky, downstream of the confluence with Boynton Slough, where the bed is extremely soft and muddy, or near the Kimlick Lane bridge where the bed is rocky and the stream depth too great.

Data collected for each piezometer include the head difference between surface water and groundwater, rate of water flow to an attached bag, length of perforated tip, and depth of perforated tip below sediment surface. Using these data, hydraulic conductivity was calculated using the following equation (after Hvorslev, 1951):

$$K = \frac{q\ln\left(\frac{L}{D} + \left(1 + \frac{L}{D}^{2}\right)^{\frac{1}{2}}\right)}{2\pi LH}$$

where K = hydraulic conductivity (cm/s)

q = volume collected over time interval (cm^3/s)

L = length of screened section (cm)

D = diameter of piezometer tube (cm)

H = head difference between groundwater and surface water (cm)

Using calculated hydraulic conductivity, discharge to streamflow per mile was calculated using a form of Darcy's Law:

$$Q = KWMI$$

where:

Q = groundwater discharge in cfs/mile

K = hydraulic conductivity in ft/s

M = a constant, 5,280 feet/mile

W = average stream width across the interval (feet)

I = head difference between groundwater and surface water over depth of screen below sediment (unitless)

For the degree of accuracy involved in the piezometer measurements and because the banks of Steamboat Creek are usually gently sloped, the stream width "W" was assumed to be a reasonable estimate of the wetted perimeter. Piezometer data are presented in Appendix 4. Calculated results are summarized in Table 11.

Each piezometer indicated an upward vertical gradient, as was expected because the creek is known to gain flow from discharged groundwater. Measured gradients ranged from 0.0031 at P6 to 0.018 at P1. Generally, the highest upward gradients were found in the Steamboat Springs vicinity. The lowest gradients were measured downstream of Short Lane, near the Huffaker Narrows.

Hydraulic conductivities calculated from constant head tests on the piezometers ranged from 4.7×10^{-3} cm per second (13ft/d) at P2 to 7.4×10^{-4} cm per second (2.1 ft/d) at P5. This range is low but within reason for the silt-sand mixture common in Steamboat Creek. Moreover, the calculated hydraulic conductivities generally decreased in a downstream direction, as would be expected as stream velocities decline and finer grained sediments drop from suspension.

Calculated hydraulic conductivity, magnitude and direction of gradient, and average stream width were used to calculate the groundwater discharge rates presented in Table 11. The calculated rates varied widely, from 0.014 cfs per mile at P6 to 0.13 cfs per mile at P2. The highest rates were generally upstream of the Huffaker Narrows, and the lowest rates were downstream of the narrows.

Concurrent with piezometer measurements, Steamboat Creek was gauged at S20, S50, S60, S80, and S100. Using previously described methods, ranges of groundwater discharge rates were calculated for the two stream reaches to compare with piezometer results. For the upper reach between S20 and S60, the piezometer results were generally well below stream gauging results. Calculated inflow at P2 was within an order of magnitude of the estimated range in groundwater discharge.

Because of the fairly small difference between flow at S80 and flow at S100, the low end of the estimated range (assuming 5 percent error) is less than zero. Calculated results for all piezometers located in this reach therefore fall within the range; however, all results are less than one-tenth of the actual measured flow increase between S80 and S100.

The piezometer method of estimating groundwater influx differs from the flow-gauging method because the gauging method averages seepage across a stream segment whereas the piezometer method estimates seepage at a single point. Because piezometer results are generally substantially less than stream gauging values, the results suggest that groundwater influx may be a point phenomenon in Steamboat Creek. In other words, relatively short stream segments with highly permeable bed material and/or large upward vertical gradients may contribute most of the observed groundwater discharge to the creek. The remainder of the streambed may transmit relatively little groundwater discharge.

Table 11
PIEZOMETER RESULTS

Piezometer					Flow Gauging	
I.D. No.	Upward Vertical Gradient	K cm/s	K ft/d	Q cfs/mi	Q cfs/mi Measured	Range
P1	0.018	1.5E-3	4.3	0.057	1.48	0.85-2.11
P2	0.0109	4.7E-3	13.0	0.13	1.48	0.85-2.11
P3	0.0089	2.2E-3	6.2	0.061	1.48	0.85-2.11
P4	0.0069	9.8E-4	2.8	0.024	0.40	-0.80-1.6
P4B	0.0046	1.9E-3	5.4	0.031	0.40	-0.80-1.6
P5	0.005	7.4E-4	2.1	0.02	0.40	-0.80-1.6
P6	0.0031	8.2E-4	2.3	0.014	0.40	-0.80-1.6

Q = estimated groundwater discharge to creek.
Range calculated assuming 5 percent error in streamflow measurement.

Sources of error accompanying the use of miniature piezometers to estimate groundwater discharge to surface water are numerous, including the assumption that the soil at the perforated tip is undisturbed, isotropic, and of infinite depth; that no sediment enters the piezometer tube; that the soil, piezometer screen, and piezometer tube are free of air or other gas; and that hydraulic losses in the piezometer and screen are negligible (Hvorslev, 1951).

Despite the fact that few of these assumptions are met in an ideal sense, the cumulative effect of the resulting error is probably insignificant when compared to the error introduced by assuming that vertical and horizontal permeabilities are equal and that streambed conditions are relatively constant.

In summary, miniature piezometer measurements made at a site meeting the criteria mentioned earlier may be relatively accurate determinations of conditions at the point of measurement. The major error is introduced when these conditions are assumed to be constant across a significant length of streambed.

6.3 CORRELATION OF TEMPERATURE VARIATION WITH GROUNDWATER DISCHARGE

The method of using variation in surface water temperatures to indicate zones of groundwater discharge has historically been used most successfully during cold weather in lakes and reservoirs where temperature measurements made over a short period of time are compared with recent measurements of groundwater flux. Because groundwater temperatures remain relatively constant throughout the year, the difference between groundwater and surface water temperatures will be greatest during cold weather when surface water temperatures are low.

The water temperature of Steamboat Creek was measured during flow gauging as part of this study. Results are listed in Appendix 1. As described in the introduction, air temperatures in the study area typically vary by several tens of degrees Fahrenheit during the day. This variation in air temperature causes surface water temperatures to rise during the day and drop at night. Because a complete gauging run along Steamboat Creek required the majority of the daylight hours, water temperature in the creek had ample time to vary during the day's gauging effort.

Because of surface water temperature variations caused by changing air temperatures, water temperature generally did not correlate well with the rate of groundwater discharge. The best correlation between stream water temperature and groundwater discharge was for the December 10, 1981, measurements, with a correlation coefficient of 0.69.

A complicating factor in correlating groundwater discharge to Steamboat Creek temperature is the influence of Steamboat Springs. In cold weather the temperature immediately downstream of Steamboat Springs was generally the highest recorded on that date for the entire creek. For example, on January 14, 1982, the temperature at S60 was 13°C, 6.5 degrees higher than S40 and 5.4 degrees higher than S70.

A possible solution to the problem of surface water temperature variation caused by variations in air temperature would be to travel the length of the stream in the early morning, making detailed surface water temperature measurements at each station to be gauged later in the day.

Because all water temperature measurements would be made while air temperature is essentially constant, variations in surface water temperature could be attributed to groundwater discharge. It might be possible, therefore, to find a greater degree of correlation between temperature variation determined in the early morning and flow variations measured later in the day.

6.4 RELATIVE QUALITY OF GROUNDWATER CONTRIBUTIONS TO STEAMBOAT CREEK

Assuming that specific conductance is a conservative property, it is possible to calculate the conductance of influent groundwater if the conductance and flow changes across a stretch of a gaining stream are known. A simple mass balance in the following form may be used:

$$SC_{gw} = \frac{(Q_o SC_o) - (Q_i SC_i)}{(Q_o - Q_i)}$$

where:

SC_{gw} = the specific conductance of influent groundwater

SC_i, SC_o = the specific conductance into and out of the stretch of interest

Q_i, Q_o = the flow into and out of the stretch of interest

To simplify the analysis, error in stream gauging results was neglected, and values of actual flow variation were used. Results of this equation on flow data from Appendix 1 are listed in Table 12. Calculated conductance varied considerably within the same interval, but a general impression of the relative quality of influent groundwater is nevertheless apparent.

The interval receiving groundwater with the highest average specific conductance was S20-S60 at about 2,400 µmho/cm. S10-S40 was similar at about 2,200 µmho/cm. The mean calculated specific conductance dropped to about 1,600 µmho/cm across S40-S60 and rose slightly to 1,900 µmho/cm across S60-S70. Across S70-S80 and S80-S100 the mean specific conductance was approximately 1,100 and 1,200 µmho/cm, respectively. Because flow decreased across the S110-S120 stretch over most of the study, it was neglected in this analysis. Last, the S130-S140 interval showed the lowest mean specific conductance at about 600 µmho/cm.

These results indicate that groundwater seeping into Steamboat Creek south of the Huffaker Narrows is high in dissolved solids, reflecting the influences of discharges from Steamboat Springs. On the other hand, the calculated mean specific conductance of groundwater entering the creek near the Trukee River confluence is relatively low,

Table 12
CALCULATED SPECIFIC CONDUCTANCE OF INFLUENT GROUNDWATER
(Micromhos/cm at 25°C)

	Interval						
Date	S10-S40	S20-S60	S40-S60	S60-S70	S70-S80	S80-S100	S130-S140
7/16/81	--	--	--	1,300	--	--	590
8/3/81	--	1,900	--	2,200	--	--	380
8/18/81	--	1,900	--	610	--	--	340
9/24/81	--	2,300	--	1,100	980	430	--
10/20/81	--	3,100	--	2,100	610	530	730
11/19/81	--	2,600	--	1,000	1,000	3,200	--
12/10/81	2,900	--	1,800	3,600	1,100	990	430
1/14/82	2,300	--	2,000	2,400	1,400	830	--
2/2/82	2,500	--	2,300	2,300	1,500	460	770
2/18/82	1,600	--	1,000	1,800	1,100	2,200	--
3/9/82	1,900	--	--	2,400	1,200	850	1,000
4/6/82	2,200	--	1,100	2,100	1,300	--	520

slightly less than the average specific conductance of nonthermal groundwater in the South Truckee Meadows. These data suggest that Steamboat Springs has little effect on groundwater and surface water quality north of Huffaker Narrows.

In summary, calculated groundwater specific conductance generally was highest adjacent to Steamboat Springs, decreasing downstream and reaching a low near the confluence with the Truckee River. This is in agreement with specific conductance maps of groundwater in the Truckee Meadows prepared by WRC (1971).

The total discharge of the Steamboat Springs thermal system to the South Truckee Meadows can be estimated from the average groundwater discharge data presented in Section 6.1 and the average specific conductance values calculated previously in this section. Hot spring discharges are calculated by:

$$Q_{\text{hot springs}} = Q_{\text{influent g.w.}} \frac{(SC_{\text{influent g.w.}} - SC_{\text{cool g.w.}})}{(SC_{\text{hot springs}} - SC_{\text{cool g.w.}})}$$

where:

$Q_{\text{hot springs}}$ = The discharge of the Steamboat Springs system

$Q_{\text{influent g.w.}}$ = Average rate of groundwater discharge to a specific interval.

$SC_{influent\ g.w.}$ = Average specific conductance of groundwater discharged to a specific interval.

$SC_{cool\ g.w.}$ = Average specific conductance of nonthermal groundwater in the South Truckee Meadows (670 μmho/cm from Table 3)

$SC_{hot\ springs}$ = Average specific conductance of the Steamboat hot springs [3,200 μmho/cm from White (1968)]

Using this equation, the values of hot spring discharge in Table 13 were calculated.

Table 13
AVERAGE TOTAL DISCHARGE FROM STEAMBOAT SPRINGS

Interval	Q Influent gw (cfs)	SC Influent gw (μmho/cm)	Q Thermal (cfs)	Q Nonthermal (cfs)
S10-S40	0.73	2,200	0.44	0.29
S40-S60	0.73	1,600	0.26	0.47
S60-S70	0.59	1,900	0.29	0.30
S70-S80	11	1,100	1.90	9.1

Total $Q_{thermal}$ = 2.9 cfs = 1,300 gpm.

The estimated total hot spring discharge of 1,300 gpm is slightly greater than the 1,130 gpm estimated by White (1968). The difference is probably because of the assumption that Steamboat Springs is the only source of water in the South Truckee Meadows with a specific conductance exceeding 670 μmho/cm. Neglecting to account for high-specific conductance water contributed by irrigation runoff or other sources results in an estimate of hot spring discharge that is higher than actual.

6.5 SOURCES OF BORON AND ARSENIC

Aqueous boron in the study area has historically been attributed to discharges from the Steamboat Springs system. A study of the B:Cl relationship in waters of the area supports this assumption. Chloride is a reasonable indicator to use because nearly all chloride in the study area originates in hot spring discharges. Furthermore, the chloride ion is highly mobile and is not known to participate to any significant degree in oxidation-reduction reactions, adsorption, or biological processes (Feth, 1981). If the assumption that essentially all boron originates from the Steamboat Springs system is invalid, the relationship between boron and chloride would logically be expected to vary throughout the study area.

Figure 13 is a plot of chloride concentration versus boron concentration for waters of South Truckee Meadows. The plot is nearly linear with a correlation coefficient of 0.967. The high correlation between chloride and boron concentrations supports White's (1968) assumption that the Steamboat Springs system is the primary source of boron in the study area.

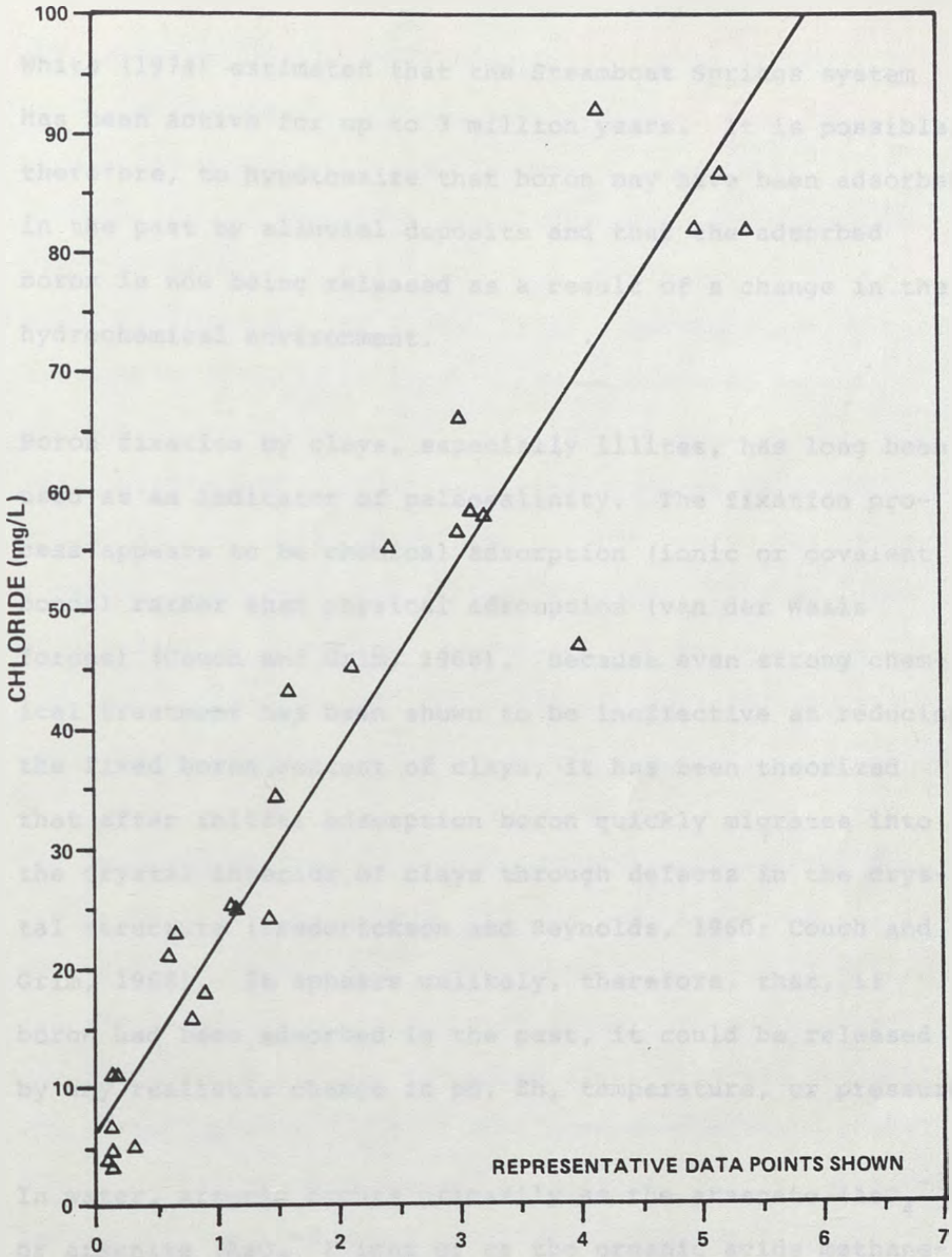

Figure 13
BORON VS. CHLORIDE FOR WATERS OF SOUTH TRUCKEE MEADOWS

White (1974) estimated that the Steamboat Springs system has been active for up to 3 million years. It is possible, therefore, to hypothesize that boron may have been adsorbed in the past by alluvial deposits and that the adsorbed boron is now being released as a result of a change in the hydrochemical environment.

Boron fixation by clays, especially illites, has long been used as an indicator of paleosalinity. The fixation process appears to be chemical adsorption (ionic or covalent bonds) rather than physical adsorption (van der Waals forces) (Couch and Grim, 1968). Because even strong chemical treatment has been shown to be ineffective at reducing the fixed boron content of clays, it has been theorized that after initial adsorption boron quickly migrates into the crystal interior of clays through defects in the crystal structure (Frederickson and Reynolds, 1960; Couch and Grim, 1968). It appears unlikely, therefore, that, if boron had been adsorbed in the past, it could be released by any realistic change in pH, Eh, temperature, or pressure.

In water, arsenic occurs primarily as the arsenate (AsO_4^{-3}) or arsenite (AsO_3^{-3}) ions or as the organic acids methanearsenic acid ($CH_3AsO(OH_2)$) and dimethyl arsenic acid ($(CH_3)_2AsOOH$) (Holm et al., 1979). The most mobile form of arsenic is arsenite in a mildly reducing environment

(Ferguson and Gavis, 1972). In oxidizing or strongly reducing environments, arsenic may be removed from solution by several processes including coprecipitation with and adsorption onto amorphous iron hydroxides, adsorption by aluminum hydroxides and clays, and precipitation as sulfides (Ferguson and Gavis, 1972). According to Holm et al. (1979), arsenic is likelier to be adsorbed on the surface of organic and inorganic substrates than removed as a crystalline precipitate. Pierce and Moore (1980) showed that arsenite adsorption by iron hydroxides reached a peak around pH = 7 and decreased as pH either increased or decreased. Eh and pH, as well as ambient iron and sulfur concentrations, will therefore strongly influence the mobility of arsenic.

Two possible sources of arsenic occur in the study area. The hydrothermally altered rocks of the Virginia Range may release arsenic to acidic waters occurring in that area, and the Steamboat Springs system appears to contribute significant quantities of aqueous arsenic to the surrounding area. Scheibach (1975) concluded that altered rocks along the valley margins, and to a lesser extent the Steamboat Springs system, were the primary sources of sulfate in the southern part of Truckee Meadows. An analysis of the $As:SO_4$ ratio in the area suggests that Steamboat Springs discharges are the most important source in the area.

After dividing the valley into three sections--the edge bordering the Virginia Range, the section adjacent to the Steamboat Hills, and the remaining area toward the center of the valley and downgradient of the possible source areas--the average $As:SO_4$ ratio characteristic of waters from each area was determined. The average ratio in the immediate vicinity of Steamboat Springs is 1.4×10^{-2}. This is consistent with the average valley ratio of 5.5×10^{-3}, whereas the average ratio near the Virginia Range is approximately 100 to 1,000 times smaller at 2.8×10^{-5}. It therefore appears that the Steamboat Springs system is the primary source of arsenic in the study area, probably with a smaller, less important contribution from the Virginia Range.

Unlike boron adsorption by clays, most of the mechanisms attenuating arsenic concentrations in water are easily reversible. The possibility of subsequent arsenic desorption due to hydrochemical changes therefore becomes very important. Matisoft et al. (1982) found that excessive arsenic concentrations in groundwater of northeastern Ohio were probably caused by a lowering of Eh, resulting in desorption of both iron and its adsorbed arsenic.

Existing chemical data are currently insufficient to determine if a similar process is occurring in the study area. Concomitant determinations of Fe and As would be very useful, and an estimation of Eh using the As(V):As(III) ratio as described by Cherry et al. (1979) would allow the hydrochemical environment in South Truckee Meadows to be more completely characterized.

7.0 SUMMARY AND CONCLUSIONS

Steamboat Creek gains flow from discharged groundwater throughout its length in the Truckee Meadows. Flow measurements with a current meter indicate that the rate of groundwater seepage to the creek is greatest adjacent to Steamboat Springs, south of Huffaker Narrows, and near the Truckee River confluence. A flow loss detected between Boynton Slough and Yori Drain (S110-S120) was probably due to an overlooked diversion. No seasonal trend in estimated groundwater seepage was noted. The mean groundwater discharge to Steamboat Creek between the USGS gauge near Steamboat and the Watermaster gauge near the Truckee River confluence was estimated to be within the range of 7.1 cfs to 28 cfs, with a mean of 17 cfs or 12,500 af/y.

Miniature piezometers were used to estimate groundwater influx by measuring head gradients and streambed permeabilities. The resulting estimates of groundwater seepage were one to two orders of magnitude less than corresponding seepage estimates from flow variation. This result suggests that groundwater influx in Steamboat Creek may be a point phenomenon.

Temperature variation across an interval correlated poorly with flow variation. The lack of correlation was attributed to surface water temperature variations caused by changing air temperatures. Localized warming in the vicinity of Steamboat Springs also complicates the use of temperature variation to identify groundwater seepage in Steamboat Creek.

The calculated specific conductance of discharged groundwater was generally highest adjacent to Steamboat Springs (2,400 μmho/cm), decreasing more or less consistently to a minimum near the Truckee River (600 μmho/cm). Using an average measured specific conductance of 3,200 μmho/cm for Steamboat Springs water (White, 1968), a total spring discharge of 1,300 gpm was calculated from specific conductance and flow data. This is somewhat higher than the 1,130 gpm calculated by White (1968) from chloride data, probably because the specific conductance method did not account for the water quality contributions of surface runoff.

The high correlation of boron versus chloride in the South Truckee Meadows supports the conclusion that the Steamboat Springs system is the source of boron in waters of the study area. Because of the strength of boron adsorption by clays, it appears unlikely that significant quantities of previously adsorbed boron could be released by any realistic change in pH, Eh, temperature, or pressure.

The As:SO_4 ratio of waters in the central part of the study area is much closer to the ratio near Steamboat Springs than the ratio near the Virginia Range. This is consistent with the assumption that Steamboat Springs is the principal source of aqueous arsenic in the study area. The ratios do suggest that the Virginia Range contributes minor but detectable amounts of arsenic to the central part of the South Truckee Meadows.

Available data are currently insufficient to determine if any previously adsorbed arsenic is being released because of changes in the hydrogeochemical environment.

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Appendix 1
CURRENT METER DISCHARGE MEASUREMENTS

Station	Date	Discharge (cfs)	Specific Conductance (μmho/cm)	Temperature °C
S10	7/16/81	0.83	280	13.0
S20	7/16/81	22.8	105	17.0
S30	7/16/81	9.01	120	18.0
S50	7/16/81	7.24	212	20.0
S70	7/16/81	0.15	1,300	21.0
S77A	7/16/81	1.34	1,200	24.0
S90	7/16/81	1.70	1,200	24.0
S100	7/22/81	3.17	611	17.0
S110	7/22/81	26.9	332	17.0
S120	7/22/81	26.2	322	18.0
S130	7/22/81	40.3	325	20.0
S140	7/22/81	44.0	347	20.0
S10	8/3/81	0.23	431	13.0
S20	8/3/81	16.8	114	15.0
S30	8/3/81	7.39	130	16.0
S50	8/3/81	9.68	278	19.0
S60	8/3/81	0.79	334	21.0
S70	8/3/81	0.87	506	21.0
S77A	8/3/81	1.04	1,430	21.0
S90	8/3/81	1.36	605	24.0
S100	8/3/81	3.94	750	28.0
S110	8/3/81	35.3	325	23.0
S120	8/3/81	36.6	321	24.0
S130	8/3/81	42.8	295	25.0
S140	8/3/81	42.9	330	24.0
S10	8/18/81	0.26	447	15.0
S20	8/18/81	21.9	115	17.0
S30	8/18/81	8.06	142	18.0
S50	8/18/81	15.0	254	20.0
S60	8/18/81	0.13	254	20.0
S70	8/18/81	0.97	560	21.0
S77A	8/18/81	1.59	1,348	20.0
S90	8/18/81	2.87	378	22.0
S100	8/18/81	5.36	784	25.0
S110	8/18/81	32.1	322	25.0
S120	8/18/81	30.3	578	22.0
S130	8/18/81	36.8	312	23.0
S140	8/18/81	41.0	315	23.0
S10	9/24/81	1.52	277	8.2
S20	9/24/81	19.3	120	10.5
S30	9/24/81	6.43	137	11.3
S50	9/24/81	13.8	292	13.0
S60	9/24/81	0.23	285	13.5

Station	Date	Discharge (cfs)	Specific Conductance (μmho/cm)	Temperature °C
S70	9/24/81	0.79	854	13.5
S80	9/24/81	19.4	897	14.1
S90	9/24/81	3.94	602	15.0
S100	9/24/81	21.2	858	13.5
S110	9/24/81	43.8	447	13.5
S120	9/24/81	41.5	320	12.0
S130	9/24/81	56.4	458	12.0
S140	9/24/81	TD	--	--
S10	10/20/81	1.27	180	6.0
S20	10/20/81	15.6	80	9.0
S30	10/20/81	6.27	97	10.0
S50	10/20/81	9.89	245	13.0
S70	10/20/81	0.28	2,100	17.0
S80	10/20/81	13.7	538	12.0
S90	10/20/81	3.80	247	13.0
S100	10/20/81	25.7	535	13.0
S110	10/20/81	46.2	380	13.0
S120	10/21/81	44.1	515	10.0
S130	10/21/81	48.7	385	11.0
S140	10/21/81	49.6	391	11.0
S10	11/19/81	6.41	302	5.0
S20	11/19/81	6.48	307	6.0
S50	11/19/81	6.83	427	12.0
S70	11/19/81	0.97	1,025	12.0
S80	11/19/81	26.5	888	9.8
S90	11/19/81	8.43	564	9.0
S100	11/19/81	27.9	1,040	8.7
S110	11/19/81	47.6	728	9.0
S120	11/20/81	42.3	993	9.0
S130	11/20/81	45.0	763	9.0
S140	11/20/81	46.7	732	9.0
S10	12/10/81	4.20	334	5.0
S40	12/10/81	5.02	752	10.0
S50	12/10/81	5.43	830	10.6
S70	12/10/81	0.43	3.640	11.4
S80	12/10/81	19.6	1,077	8.6
S90	12/10/81	5.27	854	8.7
S100	12/10/81	20.9	1,072	8.2
S110	12/10/81	32.0	864	7.8
S120	12/10/81	29.3	1,069	7.7
S130	12/11/81	32.3	855	7.3
S140	12/11/81	37.7	795	6.4
S10	1/14/82	8.07	331	2.0
S40	1/14/82	8.77	486	6.5
S60	1/14/82	9.24	562	13.0

Station	Date	Discharge (cfs)	Specific Conductance (μmho/cm)	Temperature °C
S70	1/14/82	10.4	765	7.6
S80	1/14/82	26.3	1,102	5.3
S90	1/14/82	2.48	782	6.5
S100	1/14/82	28.0	1,085	4.3
S110	1/14/82	44.7	959	4.5
S120	1/14/82	40.1	1,190	4.6
S130	1/14/82	42.7	958	4.6
S140	1/14/82	TD	--	--
S10	2/2/82	5.99	313	3.4
S40	2/2/82	6.87	588	8.2
S60	2/2/82	7.05	759	8.4
S70	2/2/82	7.69	990	8.6
S80	2/2/82	21.4	1,228	8.2
S90	2/2/82	1.81	725	8.5
S100	2/2/82	23.2	1,167	8.1
S110	2/2/82	43.8	871	8.8
S120	2/2/82	41.3	1,165	9.1
S130	2/2/82	44.4	861	9.0
S140	2/2/82	47.0	856	8.7
S10	2/18/82	29.0	183	13.7
S40	2/18/82	30.0	231	6.1
S60	2/18/82	32.9	299	6.3
S70	2/18/82	33.2	314	7.1
S80	2/18/82	80.2	589	10.3
S90	2/18/82	19.7	322	10.0
S100	2/18/82	82.2	627	9.7
S110	2/19/82	107	618	10.2
S120	2/19/82	97.9	770	9.6
S130	2/19/82	106	624	10.7
S140	2/19/82	TD	--	--
S10	3/9/82	9.11	282	6.0
S40	3/9/82	9.79	395	11.2
S60	3/9/82	8.92	673	12.0
S70	3/9/82	9.61	799	12.3
S80	3/9/82	24.8	967	13.3
S90	3/9/82	2.26	457	12.7
S100	3/9/82	26.1	961	12.0
S110	3/9/82	43.5	762	12.0
S120	3/9/82	43.3	937	12.9
S130	3/9/82	44.8	765	12.6
S140	3/9/82	46.0	771	12.1
S10	4/6/82	35.6	299	5.4
S40	4/6/82	35.9	314	7.6
S60	4/6/82	37.2	342	8.5
S70	4/6/82	38.2	387	9.2

Station	Date	Discharge (cfs)	Specific Conductance (μmho/cm)	Temperature °C
S80	4/8/82	57.5	621	6.4
S90	4/8/82	4.20	397	6.7
S100	4/8/82	48.5	627	7.3
S110	4/8/82	63.5	593	7.8
S120	4/8/82	64.4	598	8.0
S130	4/8/82	63.7	593	9.8
S140	4/8/82	67.3	589	10.0
S70	10/19/82	18.0	660	8.5
S71A	10/19/82	0.51	285	8.9
S71	10/19/82	18.8	651	8.5
S72A	10/19/82	0.26	220	9.0
S72B	10/19/82	1.04	--	--
S72	10/19/82	18.6	697	9.0
S73	10/19/82	20.4	809	9.5
S74	10/19/82	23.0	823	9.8
S74A	10/19/82	11.6	--	--
S75	10/19/82	13.3	961	10.0
S75A	10/19/82	2.07	452	9.2
S75B	10/19/82	0.90	627	10.0
S76	10/19/82	17.5	803	9.2
S90	10/19/82	8.56	590	9.5
S77	10/19/82	18.2	800	9.0
S77A	10/19/82	13.4	789	9.2
S80	10/19/82	38.7	792	9.1

TD = Stream too deep to wade.
Specific conductance measurements converted to equivalent values at 25°C using data from WRC (1979).

Appendix 2
RESULTS OF WATER ANALYSES
LABORATORY: DESERT RESEARCH INSTITUTE

Site Number	Date	pH	Sp. Cond	HC03	Cl	S04	Na	K	Ca	Mg	B	As
S10	8-25-82	7.65	237	138	6.9	3	16.5	5.22	22.1	6.43	0.09	0.005
S20	8-25-82	7.65	156	86.4	4.6	3.1	10.3	2.99	14.7	4.47	0.12	0.004
S40	8-25-82	---	---	---	---	---	---	---	---	---	0.88	0.05
S60	8-25-82	7.68	244	95.6	24.5	5.9	26	4.35	15	4.52	1.2	0.07
S60A	8-25-82	---	---	---	---	---	---	---	---	---	1.6	0.07
S70	8-25-82	7.81	322	102	42.8	9.6	40.7	5.8	15.3	4.31	2.7	0.1
S70A	8-25-82	---	---	---	---	---	---	---	---	---	5.8	0.24
S80	8-25-82	8.04	670	218	84.2	30.3	96.6	14	25.3	7.19	5.4	0.11
S10	12-6-82	8.06	340	200	11	11.4	38.4	6.34	26.9	8.6	0.09	0.005
S20	12-6-82	8.04	343	200	10.9	8.2	37.2	6.27	26	8.31	0.12	0.004
S60	12-6-82	7.97	373	202	17.9	9.4	42.6	6.63	25.9	8.29	0.97	0.03
S70	12-6-82	8.12	399	203	24	12.3	47.2	7.27	26.2	8.46	1.4	0.05
S80	12-6-82	8.14	574	236	56.9	22.3	77.9	9.61	28	10.4	3	0.08
SW1	12-10-82	---	---	---	---	---	---	---	---	---	0.17	0.015
SW2	12-10-82	7.29	896	290	131	22.8	160	15.6	22.9	1.86	8.5	0.4
SW3	12-10-82	6.86	272	164	3.7	3.6	8.31	3.98	35.2	7.84	0.1	§0.002
SW4	12-10-82	---	---	---	---	---	---	---	---	---	0.1	0.002
SE1	12-13-82	7.55	930	341	103	31.9	197	16.7	4.07	1.03	7.1	0.21
SE2	12-13-82	---	---	---	---	---	---	---	---	---	0.18	0.005
SE3	12-13-82	7.09	1420	122	4.6	677	94.7	5.17	148	56.4	0.2	0.003
SE4	12-13-82	---	---	---	---	---	---	---	---	---	0.16	0.002

Notes:
1. Results expressed as mg/L.
2. --- indicates analysis not requested.

Appendix 3
DESCRIPTIONS OF SAMPLING AND GAUGING SITES

Site Number	Location Description
S10	Steamboat Creek approximately 10 yards upstream of the USGS gauge at Steamboat
S20	Steamboat Creek approximately 50 yards downstream of the confluence with Steamboat Ditch.
S30	Chandler Ditch 10 yards downstream of the culvert beneath Towne Drive
S40	Steamboat Creek approximately 150 yards upstream of the Steamboat Post Office on Towne Drive
S50	Crane Ditch in concrete structure, approximately 20 yards downstream of the diversion itself
S60	Leakage from the Crane Ditch diversion
S60A	Steamboat Creek approximately 1/3 mile upstream of the S.R. 342 culverts
S70	Steamboat Creek approximately 20 yards downstream of the triple culverts beneath State Route 341 (formerly State Route 17, also known as Geiger Grade)
S70A	Steamboat Creek due east of the Mays Lane terminus
S71A	Small ditch tributary to Steamboat Creek at SE 1/4 SEC 21 T18N R20E
S71	Steamboat Creek approximately 20 yards downstream of small ditch described at S71A
S72A	Small ditch tributary to Steamboat Creek at NE 1/4 SEC 21 T18N R20E
S72B	Diversion ditch at NE 1/4 SEC 21 T18N R20E
S72	Steamboat Creek approximately 10 yards downstream of diversion described at S72B
S73	Steamboat Creek at SE 1/4 SEC 16 T18N R20E, approximately 25 yards downstream of 90-degree bend in the creek
S74	Steamboat Creek approximately 100 yards upstream of the large diversion described at S74A

Site Number	Location Description
S74A	Major diversion at SW 1/4 SEC 10 T18N R20E
S75	Steamboat Creek approximately 20 yards upstream of the return ditch described at S75A
S75A	Tributary ditch to Steamboat Creek at E 1/2 SEC 3 T18N R20E
S75B	Small return to Steamboat Creek from the north, located at NE 1/4 SEC 3 T18N R20E
S76	Steamboat Creek approximately 30 yards downstream of return at S75B and of 90-degree bend in creek bed
S77	Steamboat Creek approximately 50 yards upstream of the culverts at Short Lane
S77A	Major return to Steamboat Creek, gauged approximately 50 yards upstream of its confluence with the creek
S90	Alexander Lake Ditch approximately 20 yards upstream of Short Lane
S80	Steamboat Creek approximately 75 yards downstream of Short Lane
S100	Steamboat Creek approximately 25 yards upstream of the confluence with Boynton Slough
S110	Steamboat Creek approximately 50 yards downstream of the confluence with Boynton Slough
S120	Steamboat Creek approximately 20 yards upstream of the Yori Drain confluence
S130	Steamboat Creek approximately 50 yards downstream of the Yori Drain confluence
S140	Steamboat Creek approximately 20 yards upstream of the Kimlick Lane bridge
SE1	A well located at SW 1/4 NW 1/4 SEC 28 T18N R20E. Street address: 14630 Toll Road
SE2	A well located at SW 1/4 SE 1/4 SEC 27 T18N R20E. Street address: 16190 Kivett Lane

Site Number	Location Description
SE3	A well located at NE 1/4 NW 1/4 NW 1/4 SEC 34 T18N R20#. Street address: 16220 Pinion Drive
SE4	A well located at SE 1/4 NW 1/4 NW 1/4 SEC 34 T18N R20E. Street address: 1855 State Route 341
SW1	A well located at NW 1/4 NW 1/4 SEC 28 T18N R20E. Street address: 190 Whites Creek Lane
SW2	A well located at SW 1/4 NE 14/SEC 29 T18N R20E. Street address: 1325 State Route 431
SW3	A well located at NE 1/4 NW 1/4 SEC 29 T18N R20E. Street address: 1660 Whites Creek Lane
SW4	A well located at SE 1/4 NW 1/4 SEC 30 T18N R20E. Street: Whites Creek Lane

Appendix 4
PIEZOMETER FIELD DATA

Piezometer Number	Stream head[a] (cm)	Ground-water head[a] (cm)	Vol (ml)	Time		Screen Depth (cm)	Stream Width (ft)
P1	80.80	82.42	4.5	31	min	90	12.0
P2	53.50	54.59	13.5	45	min	100	15.0
P3	78.10	78.90	6.6	65	min	90	18.0
P4	75.90	76.49	4.0	120	min	85	20.5
P4B	64.00	64.46	7.4	45	min	100	20.5
P5	62.37	62.87	2.2	58	hr	100	33.0
P6	74.20	74.51	9.0	30.5	hr	100	31.5

[a]Arbitrary datum.